## Search for high mass dilepton resonances in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS experiment

## The ATLAS Collaboration

This article presents a search for high mass  $e^+e^-$  or  $\mu^+\mu^-$  resonances in pp collisions at  $\sqrt{s}=7$  TeV at the LHC. The data were recorded by the ATLAS experiment during 2010 and correspond to a total integrated luminosity of  $\sim 40~{\rm pb^{-1}}$ . No statistically significant excess above the Standard Model expectation is observed in the search region of dilepton invariant mass above 110 GeV. Upper limits at the 95% confidence level are set on the cross section times branching ratio of Z' resonances decaying to dielectrons and dimuons as a function of the resonance mass. A lower mass limit of 1.048 TeV on the Sequential Standard Model Z' boson is derived, as well as mass limits on  $Z^*$  and  $E_6$ -motivated Z' models.

A search for high mass resonances decaying into  $e^+e^-$  or  $\mu^+\mu^-$  pairs is presented based on an analysis of 7 TeV pp collision data recorded with the ATLAS detector [1]. Among the possibilities for such resonances, this article focuses on new heavy neutral gauge bosons  $(Z',Z^*)$  [2–4]; other hypothetical states like a Randall-Sundrum spin-2 graviton [5] or a spin-1 techni-meson [6] are not discussed here, though this analysis is also sensitive to them.

The benchmark model for Z' bosons is the Sequential Standard Model (SSM) [2], in which the Z' ( $Z'_{SSM}$ ) has the same couplings to fermions as the Z boson. A more theoretically motivated model is the Grand Unification model in which the  $E_6$  gauge group is broken into SU(5) and two additional U(1) groups [7]. The lightest linear combination of the corresponding two new neutral gauge bosons,  $Z'_{\psi}$  and  $Z'_{\chi}$ , is considered the Z' candidate:  $Z'(\theta_{E_6}) = Z'_{\psi} \cos \theta_{E_6} + Z'_{\chi} \sin \theta_{E_6}$ , where  $0 \le \theta_{E_6} < \pi$ is the mixing angle between the two gauge bosons. The pattern of spontaneous symmetry breaking and the value of  $\theta_{E_6}$  determines the Z' couplings to fermions; six different models [2, 7] lead to the specific Z' states named  $Z'_{\psi}, Z'_{\rm N}, Z'_{\eta}, Z'_{\rm I}, Z'_{\rm S}$  and  $Z'_{\chi}$  respectively. Because of different couplings to u and d quarks, the ranking of the production cross sections of these six states is different in  $p\bar{p}$  and pp collisions. In this search, the resonances are assumed to have a narrow intrinsic width, comparable to the contribution from the detector mass resolution. The expected intrinsic width of the  $Z'_{\rm SSM}$  as a fraction of the mass is 3.1%, while for any  $E_6$  model the intrinsic width is predicted to be between 0.5% and 1.3% [8].

Production of a  $Z^*$  boson [4, 9] could also be detected in a dilepton resonance search. The anomalous (magnetic moment type) coupling of the  $Z^*$  boson leads to kinematic distributions different from those of the Z' boson. To fix the coupling strength, a model with quark-lepton universality, and with the total  $Z^*$  decay width equal to that of the  $Z'_{\rm SSM}$  with the same mass, is adopted [10, 11].

Previous indirect and direct searches have set constraints on the mass of Z' resonances [12–16]. The  $Z'_{\rm SSM}$  is excluded by direct searches at the Tevatron with a mass lower than 1.071 TeV [17, 18]. The large center

of mass energy of the LHC provides an opportunity to search for Z' resonances with comparable sensitivity using the 2010 pp collision data. CMS has very recently excluded a  $Z'_{\rm SSM}$  with a mass lower than 1.140 TeV [19].

The three main detector systems of ATLAS [1] used in this analysis are the inner tracking detector, the calorimeter, and the muon spectrometer. Charged particle tracks and vertices are reconstructed with the inner detector (ID) which consists of silicon pixel, silicon strip, and transition radiation detectors covering the pseudorapidity range  $|\eta|$  < 2.5 [47]. It is immersed in a homogeneous 2 T magnetic field provided by a superconducting solenoid. The latter is surrounded by a finely-segmented, hermetic calorimeter that covers  $|\eta| < 4.9$  and provides three-dimensional reconstruction of particle showers using lead-liquid argon sampling for the electromagnetic compartment followed by a hadronic compartment which is based on iron-scintillating tiles sampling in the central region and on liquid argon sampling with copper or tungsten absorbers for  $|\eta| > 1.7$ . Outside the calorimeter, there is a muon spectrometer with air-core toroids providing a magnetic field. Three sets of drift tubes or cathode strip chambers provide precision  $(\eta)$  coordinates for momentum measurement in the region  $|\eta| < 2.5$ . Finally, resistive-plate and thin-gap chambers provide muon triggering capability.

The data sample used in this analysis was collected during 2010. Application of detector and data quality requirements leads to an available integrated luminosity of 39 pb<sup>-1</sup> and 42 pb<sup>-1</sup> for the electron and muon analyses respectively.

Triggers requiring the presence of at least one electron or muon above a transverse momentum  $(p_{\rm T})$  threshold were used to identify the events recorded for full reconstruction. The thresholds varied from 14 to 20 GeV for electrons and 10 to 13 GeV for muons depending on the luminosity. The overall trigger efficiency at the Z peak is 100% with negligible uncertainty for dielectron events and  $(98.2\pm0.3)\%$  for dimuon events, for the selection criteria presented below. The trigger-level bunch-crossing identification of very high transverse energy electron triggers relies on a special algorithm implemented in the first-

level calorimeter trigger hardware; its performance was checked with calibration data and the resulting systematic uncertainty on the trigger efficiency is  $^{+0}_{-2}\%$ . Collision candidates are selected by requiring a primary vertex with at least three associated charged particle tracks, consistent with the beam interaction region.

In the  $e^+e^-$  channel, two electron candidates are required with transverse energy  $E_T > 25$  GeV,  $|\eta| < 2.47$ ; the region  $1.37 \le |\eta| \le 1.52$  is excluded because it corresponds to a transition region between the barrel and endcap calorimeters which has degraded energy resolution. Electron candidates are formed from clusters of cells reconstructed in the electromagnetic calorimeter. Criteria on the transverse shower shape, the longitudinal leakage into the hadronic calorimeter, and the association to an inner detector track are applied to the cluster to satisfy the *Medium* electron definition [20, 21]. The electron energy is obtained from the calorimeter measurements and its direction from the associated track. A hit in the first layer of the pixel detector is required (if an active pixel layer is traversed) to suppress background from photon conversions. In addition, a fiducial cut removes events with electrons near problematic regions of the electromagnetic calorimeter during the 2010 run, reducing the acceptance by 6%. The two electron candidates are not required to have opposite charge because of possible charge mis-identification either due to bremsstrahlung or to the limited momentum resolution of the inner detector at very high  $p_{\rm T}$ . For these selection criteria, the overall event acceptance for a  $Z' \to e^+e^-$  of mass 1 TeV is 60%.

In the  $\mu^+\mu^-$  channel, two muon candidates of opposite charge are required, each satisfying  $p_T > 25$  GeV. These muons are required to be within the trigger acceptance of  $|\eta| < 2.4$ . Muon tracks are reconstructed independently in both the inner detector and muon spectrometer. The momentum is taken from a combined fit to the measurements from both subsystems. To obtain optimal momentum resolution, the muons used in this analysis are required to have at least three hits in each of the inner, middle, and outer detectors of the muon system, and at least one hit in the non-bend plane. Residual misalignments of the muon detectors, which could cause a degradation of the momentum resolution, were studied with cosmic rays and with collision data in which the muons traversed overlapping sets of muon chambers. The effect of the misalignments, and the intrinsic position resolution, are included in the simulation. Studies of muons from W decays verified that the observed momentum spectrum agrees with the simulation up to  $p_{\rm T} = 300$  GeV above which the event numbers are sparse. To suppress background from cosmic rays, the muons are also required to satisfy selections on the impact parameter,  $|d_0| < 0.2$  mm; z coordinate with respect to the primary vertex (PV),  $|z_0 - z(PV)| < 1$  mm; and on the z position of the primary vertex, |z(PV)| < 200 mm. To reduce the background from jets, each muon is required to be isolated such that  $\Sigma p_{\rm T}(\Delta R < 0.3)/p_{\rm T}(\mu) < 0.05$ , where  $\Sigma p_{\rm T}(\Delta R < 0.3)$  is the sum of the  $p_{\rm T}$  of the other

tracks in a cone  $\Delta R < 0.3$  around the direction of the muon  $(\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \varphi)^2})$ . The overall event acceptance is 40% for a  $Z' \to \mu^+ \mu^-$  of mass 1 TeV. The primary reason for the lower acceptance compared to the electron channel is the requirement that hits are observed in all three layers of muon chambers, which reduces coverage in some regions of  $\eta$ . It is expected that this acceptance difference will be recovered in the future.

For both channels, the dominant background originates with the  $Z/\gamma^*$  (Drell-Yan) process, which has the same final state as Z' or  $Z^*$  production. In the  $e^+e^-$  channel, the second largest background arises from QCD jet production including b quarks (referred to below as QCD background); above  $m_{e^+e^-}=110$  GeV, the next largest backgrounds are  $t\bar{t}$  and W + jets events. In the  $\mu^+\mu^-$  channel, in order of dominance the backgrounds are Drell-Yan production, followed by  $t\bar{t}$  and diboson (WW,WZ and ZZ) production; the QCD and W + jets backgrounds are negligible.

Expected signal and backgrounds, with the exception of the QCD component, are evaluated with simulated samples and normalized with respect to one another using the highest-order available cross section predictions. The Z' signal and  $Z/\gamma^*$  processes are generated with Pythia 6.421 [22] using MRST2007 LO\* [23] parton distribution functions (PDF's). The  $Z'_{SSM}$  was used as the benchmark signal model and this signal sample was generated with Pythia using Standard Model couplings.  $Z^*$  events are generated with CompHEP [24] using CTEQ6L1 [25] PDF's followed by PYTHIA for parton showering and underlying event generation. The diboson processes are generated with HERWIG 6.510 [26, 27] using MRST2007 LO\* PDF's. The W + jets background is generated with Alpgen [28] and the  $t\bar{t}$  background with MC@NLO 3.41 [29]. For both, JIMMY 4.31 [30] is used to describe multiple parton interactions and Her-WIG to describe the remaining underlying event and parton showers. CTEQ [25] parton distribution functions are used. For all samples, final state photon radiation is handled by Photos [31] and the interaction of particles and the response of the detector are carried out using full detector simulation [32] based on Geant4 [33].

The  $Z/\gamma^*$  cross section is calculated at next-to-nextto-leading order (NNLO) using PHOZPR [34] with MSTW2008 parton distribution functions [35]. The ratio of this cross section to the leading order cross section can be used to determine a mass dependent QCD K-factor which is applied to the results of the leading order simulations. The same QCD K-factor is applied to the Z'signal. However, the QCD K-factor is not applied to the leading-order  $Z^*$  cross section since the  $Z^*$  model uses an effective Lagrangian with a different Lorentz structure. Higher order weak corrections (beyond the photon radiation included in the simulation) are calculated using HORACE [36, 37], yielding a weak K-factor due to virtual heavy gauge boson loops. The weak K-factor is not applied to the Z' or  $Z^*$  signal since it is not universal, but depends on the coupling of the W and Z bosons to the

Z' or  $Z^*$ . The diboson cross section is known to next-to-leading order (NLO) with an uncertainty of 5%. The W+ jets cross section is calculated at NLO, and rescaled to the inclusive NNLO calculation, resulting in 30% uncertainty when at least one parton with  $E_T > 20$  GeV accompanies the W boson. The  $t\bar{t}$  cross section is predicted at approximate-NNLO, with 10% uncertainty [38–40]. Cross section uncertainties are estimated from PDF error sets and from variation of renormalization and factorization scales in the cross section calculation.

To estimate the QCD background in the  $e^+e^-$  sample, a combination of three different techniques is used. In the "reversed electron identification" technique, a sample of events where both electrons pass the *Loose* electron identification selections [20, 21] but fail the *Medium* selections is used to determine the shape of the QCD background as a function of invariant mass  $m_{e^+e^-}$ . This template shape, and the sum of the Drell-Yan, diboson,  $t\bar{t}$  and W + jets backgrounds, are fitted to the observed  $m_{e^+e^-}$ distribution to determine the normalization of the QCD contribution. In the second technique [21], the isolation distribution for the electrons (energy in the calorimeter in a cone of  $\Delta R < 0.4$  around the electron track after subtracting the electron cluster energy) is fitted to a signal template, corresponding to electrons from either Zor  $Z'/Z^*$  production, plus a background template: the latter is determined from the data by reversing electron identification selections. The third technique relates, via a matrix inversion, the measured number of events passing Loose or Medium, plus first-pixel-layer hit, identification requirements for each of the two electrons (i.e. four different categories of events) to the true number of real and fake electron combinations in the sample [41, 42]. To combine the measurements from each of these estimates and obtain the QCD background in the high- $m_{e^+e^-}$  region, a fit in several bins of  $m_{e^+e^-}$  above 110 GeV is performed using a power-law function of  $m_{e^+e^-}$  with the parameters being the exponent and the integral number of events with  $m_{e^+e^-} > 110$  GeV. The background in any given region of  $m_{e^+e^-}$  is then obtained from an integral of this function; the corresponding uncertainty is obtained by propagating the statistical and systematic uncertainties for each of the background estimation methods. A small additional systematic uncertainty related to a small bias in the fit for low statistics and variations when different functions were used is also taken into account. The power law function gives a conservative estimate of the QCD background at very large  $m_{e^+e^-}$ , as it falls less rapidly than other functional forms used to fit dijet invariant mass distributions [43].

QCD backgrounds in the  $\mu^+\mu^-$  sample can be produced by pion and kaon decay in flight or from semi-leptonic decays of b and c quarks. The former is suppressed by the small decay probability of a high- $p_{\rm T}$  pion or kaon. The background from semi-leptonic decays of b and c quarks is evaluated using the  $\Sigma p_{\rm T}(\Delta R < 0.3)/p_{\rm T}(\mu)$  isolation variable. A simulated sample of  $b\bar{b}$  and  $c\bar{c}$  events is shown to reproduce the isolation distri-

bution of the muon candidates, after all selection cuts except isolation are applied. This simulated QCD sample is normalized to the data in the region  $\Sigma p_{\rm T}(\Delta R < 0.3)/p_{\rm T}(\mu) > 0.1$ , and then used to predict the background passing the final selection criterion of  $\Sigma p_{\rm T}(\Delta R < 0.3)/p_{\rm T}(\mu) < 0.05$ . A systematic uncertainty of 50% is assigned to the QCD background to cover the difference between the number of non-isolated muons predicted by the simulation and the number observed in the data.

A direct estimate of background from cosmic rays in the muon channel is obtained by observing the rate, and mass distribution, of events satisfying  $3 < |z_0 - z(\text{PV})| < 200 \text{ mm}$  or  $|d_0| > 0.3 \text{ mm}$ . The number of events in the final sample is obtained by scaling to the number expected to pass the  $|d_0| < 0.2 \text{ mm}$ , and  $|z_0 - z(\text{PV})| < 1 \text{ mm}$  selection criteria. The total cosmic ray background above  $m_{\mu^+\mu^-} = 70 \text{ GeV}$  is thus estimated to be  $0.004 \pm 0.002$  events.

Finally, while the primary estimate of the  $t\bar{t}$  background is taken from Monte Carlo for both channels as discussed above, a data-driven cross-check of the  $t\bar{t}$  background was also performed. The  $e\mu$  final state with dilepton invariant mass > 100 GeV provides an enriched sample of  $t\bar{t}$  fully leptonic events. After correcting for relative efficiencies, it provides a direct estimate from data of the  $t\bar{t} \to e^+e^-$ ,  $\mu^+\mu^-$  backgrounds. The results, which have relatively large statistical uncertainties due to the limited number of events, are in good agreement with the Monte Carlo prediction.

The observed invariant mass distributions,  $m_{e^+e^-}$  and  $m_{\mu^+\mu^-}$ , are compared to the expectation of the SM backgrounds. To make this comparison, the sum of the Drell-Yan,  $t\bar{t}$ , diboson and W + jets backgrounds (with the relative contributions fixed according to the respective cross sections) is scaled such that when added to the data-driven QCD background, the result agrees with the observed number of data events in the 70 - 110 GeV mass interval. The advantage of this approach is that the uncertainty on the luminosity, and any mass independent uncertainties in efficiencies, cancel between the  $Z'/Z^*$  and the Z in the limit computation presented below. The integrated Drell-Yan cross section at NNLO above a generator-level dilepton invariant mass of 60 GeV is  $(0.989 \pm 0.049)$  nb.

Figure 1 presents the invariant mass  $(m_{e^+e^-})$  distribution after final selection while Table I shows the number of data events and estimated backgrounds in bins of reconstructed  $e^+e^-$  invariant mass. The dielectron invariant mass distribution is well described by the prediction from SM processes.

Similarly, Figure 2, and Table II show the results for the  $\mu^+\mu^-$  sample. Again, there is good agreement with the prediction from SM processes. Figures 1 and 2 also display expected  $Z'_{\rm SSM}$  signals for three masses around 1 TeV. Expected  $Z^*$  signals (not shown) have a similar shape and approximately 40% higher cross section. Three events in the vicinity of  $m_{e^+e^-}=600$  GeV and a single event at  $m_{\mu^+\mu^-}=768$  GeV are observed in the

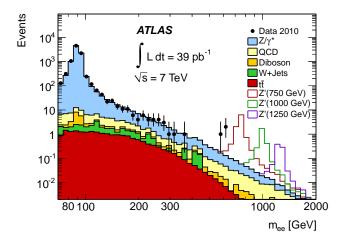


FIG. 1: Dielectron invariant mass  $(m_{e^+e^-})$  distribution after final selection, compared to the stacked sum of all expected backgrounds, with three example  $Z'_{\rm SSM}$  signals overlaid. The bin width is constant in  $\log m_{e^+e^-}$ .

TABLE I: Expected and observed number of events in the dielectron channel. The uncertainties quoted include both statistical and systematic uncertainties. The systematic uncertainties are correlated across bins and are discussed in the text. Entries of 0.0 indicate a value < 0.05.

$m_{e^+e^-}[{ m GeV}]$	70-110	110-130	130-150	150-170	170-200
$Z/\gamma^*$	$8498.5 \pm 7.9$	$104.9 \pm 3.3$	$36.8 \pm 1.3$	$19.4 \pm 0.7$	$14.7 \pm 0.6$
$tar{t}$	$8.2 \pm 0.8$	$2.8 \pm 0.3$	$2.1 \pm 0.2$	$1.7 \pm 0.2$	$1.7 \pm 0.2$
Diboson	$12.1 \pm 0.9$	$1.0 \pm 0.2$	$0.7 \pm 0.2$	$0.5 \pm 0.2$	$0.5 \pm 0.1$
W + jets	$6.0 \pm 1.8$	$3.7 \pm 1.2$	$1.2 \pm 0.5$	$1.3 \pm 0.5$	$1.2 \pm 0.4$
QCD	$32.1 \pm 7.1$	$8.4 \pm 1.8$	$5.5 \pm 0.8$	$3.2 \pm 0.6$	$2.8 \pm 0.8$
Total	$8557.0 \pm 10.8$	$120.9 \pm 4.0$	$46.4 \pm 1.6$	$26.2 \pm 1.1$	$20.8 \pm 1.1$
Data	8557	131	49	20	18
$m_{e^+e^-}[\mathrm{GeV}]$	200-240	240-300	300-400	400-800	800-2000
$Z/\gamma^*$	$9.5 \pm 0.4$	$6.0 \pm 0.3$	$3.2 \pm 0.1$	$1.6 \pm 0.1$	$0.1 \pm 0.0$
$t\bar{t}$					0.1 - 0.0
$\iota\iota$	$1.2 \pm 0.1$	$0.9 \pm 0.1$	$0.5\pm0.0$	$0.2\pm0.0$	$0.0 \pm 0.0$
Diboson	$1.2 \pm 0.1$ $0.4 \pm 0.1$	$0.9 \pm 0.1$ $0.3 \pm 0.1$	$0.5 \pm 0.0$ $0.2 \pm 0.1$	$0.2 \pm 0.0$ $0.1 \pm 0.1$	
				0 0.0	$0.0 \pm 0.0$
Diboson	$0.4 \pm 0.1$	$0.3 \pm 0.1$	$0.2\pm0.1$	$0.1 \pm 0.1$	$0.0 \pm 0.0 \\ 0.0 \pm 0.0$
$\begin{array}{c} {\rm Diboson} \\ W+{\rm jets} \end{array}$	$0.4 \pm 0.1$ $1.1 \pm 0.4$	$0.3 \pm 0.1 \\ 0.3 \pm 0.1$	$0.2 \pm 0.1 \\ 0.2 \pm 0.1$	$0.1 \pm 0.1$ $0.2 \pm 0.1$	$0.0 \pm 0.0$ $0.0 \pm 0.0$ $0.0 \pm 0.0$

data. The p-value which quantifies, in the absence of signal, the probability of observing an excess anywhere in the search region  $m_{\ell^+\ell^-} > 110$  GeV ( $\ell = e$  or  $\mu$ ), with a significance at least as great as that observed in the data is evaluated [44]. Since the resulting p-values are 5% and 22% for the electron and muon channels, respectively, no statistically significant excess above the predictions of the SM has been observed.

Given the absence of a signal, an upper limit on the number of Z' events is determined at the 95% confidence level (C.L.) using a Bayesian approach [44]. The invariant mass distribution of the data is compared to templates of the expected backgrounds and varying amounts of signal at varying pole masses in the 0.13-2.0 TeV range, a technique used in Ref. [45]. A likelihood function is defined as the product of the Poisson probabilities over all mass bins in the search region, where the Poisson probability in each bin is evaluated for the observed number

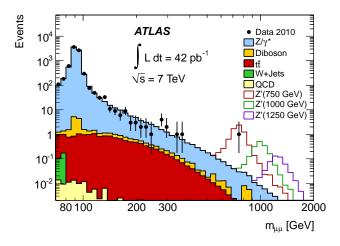


FIG. 2: Dimuon invariant mass  $(m_{\mu^+\mu^-})$  distribution after final selection, compared to the stacked sum of all expected backgrounds, with three example  $Z'_{\rm SSM}$  signals overlaid. The bin width is constant in  $\log m_{\mu^+\mu^-}$ .

TABLE II: Expected and observed number of events in the dimuon channel. The uncertainties quoted include both statistical and systematic uncertainties. The systematic uncertainties are correlated across bins and are discussed in the text. Entries of 0.0 indicate a value < 0.05.

$m_{\mu^+\mu^-}[\text{GeV}]$	70-110	110-130	130-150	150-170	170-200
$Z/\gamma^*$	$7546.7 \pm 7.1$	$98.4 \pm 3.1$	$33.4 \pm 1.1$	$17.2 \pm 0.6$	$12.8 \pm 0.5$
$t ar{t}$	$6.0 \pm 0.6$	$2.4 \pm 0.3$	$1.7 \pm 0.2$	$1.2 \pm 0.1$	$1.2 \pm 0.1$
Diboson	$10.0 \pm 0.5$	$0.8 \pm 0.1$	$0.6 \pm 0.0$	$0.5 \pm 0.0$	$0.4 \pm 0.0$
W + jets	$0.3 \pm 0.2$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
QCD	$0.1 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
Total	$7563.0 \pm 7.2$	$101.6 \pm 3.1$	$35.7 \pm 1.2$	$18.9 \pm 0.7$	$14.4 \pm 0.5$
Data	7563	101	41	11	11
$m_{\mu^+\mu^-}[\text{GeV}]$	200-240	240-300	300-400	400-800	800-2000
$Z/\gamma^*$	$7.8 \pm 0.3$	$5.1 \pm 0.2$	$2.5 \pm 0.1$	$1.3 \pm 0.1$	$0.1 \pm 0.0$
$t ar{t}$	$1.0 \pm 0.1$	$0.7 \pm 0.1$	$0.4 \pm 0.0$	$0.1 \pm 0.0$	$0.0 \pm 0.0$
Diboson	$0.3 \pm 0.0$	$0.2 \pm 0.0$	$0.2 \pm 0.0$	$0.1 \pm 0.0$	$0.0 \pm 0.0$
W + jets	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
QCD	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
Total	$9.1 \pm 0.4$	$6.0 \pm 0.2$	$3.0 \pm 0.1$	$1.5 \pm 0.1$	$0.1 \pm 0.0$
Data	7	6	2	1	0

of data events given the expectation from the template. The total acceptance for signal as a function of mass is propagated into the expectation. For each Z' pole mass, a uniform prior in the Z' cross section is used.

The normalization procedure described above makes this analysis insensitive to the uncertainty on the integrated luminosity as well as other mass-independent systematic uncertainties. Mass-dependent systematic uncertainties are incorporated as nuisance parameters whose variation is integrated over in the computation of the likelihood function [44]. The relevant systematic uncertainties are reconstruction efficiency, QCD and weak K-factors, PDF and resolution uncertainties. These uncertainties are correlated across all bins in the search region, and they are correlated between signal and background except for the weak K-factor which is only applied to the Drell-Yan background. In addition, there is an uncertainty on the QCD component of the background for the

TABLE III: Summary of systematic uncertainties on the expected numbers of events at  $m_{\ell^+\ell^-} = 1$  TeV. NA indicates that the uncertainty is not applicable, and "-" denotes a negligible entry.

Source	dielectrons		dimuons		
	Z' signal	background	Z' signal	background	
Normalization	5%	5%	5%	5%	
PDFs	6%	6%	6%	6%	
QCD K-factor	3%	3%	3%	3%	
Weak K-factor	NA	4.5%	NA	4.5%	
Efficiency	-	-	3%	3%	
Resolution	-	-	3%	3%	
Total	9.4%	9.5%	9.4%	10.4%	

electron channel.

The uncertainties on the mass-dependent nuisance parameters are as follows: since the total background is normalized to the data in the region of the  $Z \to \ell^+\ell^-$  mass peak, the residual systematic uncertainties are small at low mass and grow at high mass. The dominant uncertainties are of a theoretical nature. The uncertainty on the cross sections due to PDF variation is 6% (8%) at 1 TeV for  $Z'(Z^*)$  production, for both channels. The uncertainties on the QCD and weak K-factors are 3% and 4.5% respectively for both channels. The uncertainty in the weak K-factor includes the effects of neglecting real boson emission, the difference in the electroweak scheme definition between PYTHIA and HORACE, and higher order electroweak and  $\mathcal{O}(\alpha\alpha_s)$  corrections. Finally, an uncertainty of 5%, due to the uncertainty on the  $Z/\gamma^*$  cross section in the normalization region, as well as a 1% statistical error on the data in the normalization region, are applied.

On the experimental side, the systematic effects are as follows. In the electron channel, the calorimeter resolution is dominated at large transverse energy by a constant term which is 1.1% in the barrel and 1.8% in the endcaps with a small uncertainty. The simulation was adjusted to reproduce this resolution at high energy and the uncertainty on it has a negligible effect. The calorimeter energy calibration uncertainty is between 0.5% and 1.5% depending on transverse momentum and pseudorapidity. The non-linearity of the calorimeter response is negligible according to test beam data and Monte Carlo studies [46]. The uncertainty on the energy calibration has minimal impact on the sensitivity of the search, since its main effect is a shift of a potential peak in dilepton mass without change of the line-shape. No source of efficiency variation for electron reconstruction and identification at high  $p_{\rm T}$  has been found.

For the muon channel, the combined uncertainty on the trigger and reconstruction efficiency is estimated to be 3% at 1 TeV. This uncertainty is dominated by the rate of muon bremsstrahlung in the calorimeter which may interfere with reconstruction in the muon spectrometer. The uncertainty on the resolution due to residual misalignments in the muon spectrometer propagates to

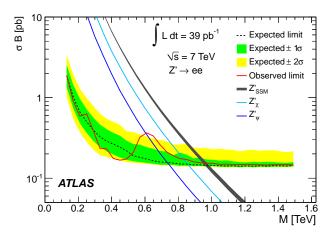


FIG. 3: Expected and observed 95% C.L. limits on  $\sigma B$  and expected  $\sigma B$  for  $Z'_{\rm SSM}$  production and the two  $E_6$ -motivated Z' models with lowest and highest  $\sigma B$  for the dielectron channel. The thickness of the SSM theory curve represents the theoretical uncertainty and holds for the other theory curves.

a change in the observed width of  $Z'/Z^*$  line-shape, and affects the sensitivity by 3%. The muon momentum scale is calibrated with a statistical precision of 0.2% using the  $Z \to \ell^+\ell^-$  mass peak. As with the electron channel, the momentum calibration uncertainty has negligible impact in the muon channel search. The systematic uncertainties are summarized in Table III.

The limit on the number of Z' events produced is converted into a limit on cross section times branching ratio  $\sigma B(Z' \to \ell^+ \ell^-)$  by scaling with the observed number of Z boson events and the known value of  $\sigma B(Z \to \ell^+ \ell^-)$ . The expected exclusion limits are determined using simulated pseudo-experiments containing only Standard Model processes by evaluating the 95% C.L. upper limits for each pseudo-experiment for each fixed value of  $M_{Z'}$ . The median of the distribution of limits is chosen to represent the expected limit. The ensemble of limits is also used to find the 68% and 95% envelope of the expected limits as a function of  $M_{Z'}$ .

Figure 3 shows for the dielectron channel the 95% C.L. observed and expected exclusion limits on  $\sigma B$ . It also shows the theoretical cross section times branching ratio for the  $Z'_{\rm SSM}$  and for the lowest and highest  $\sigma B$  of  $E_6$ -motivated Z' models. Similarly, Figure 4 shows the same results in the case of the dimuon channel. Figure 5 shows the 95% C.L. exclusion limit on  $\sigma B$  for the combination of the electron and muon channels. The combination is performed by defining the likelihood function in terms of the total number of Z' events produced in both channels.

In the three cases (dielectron, dimuon and combined channels), the 95% C.L.  $\sigma B$  limit is used to set mass limits for each of the considered models. Mass limits obtained for the  $Z'_{\rm SSM}$  are displayed in Table IV together with the corresponding  $\sigma B$  limit. The combined

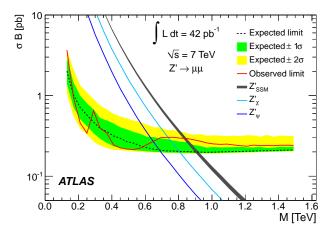


FIG. 4: Expected and observed 95% C.L. limits on  $\sigma B$  and expected  $\sigma B$  for  $Z'_{\rm SSM}$  production and the two  $E_6$ -motivated Z' models with lowest and highest  $\sigma B$  for the dimuon channel. The thickness of the SSM theory curve represents the theoretical uncertainty and holds for the other theory curves.

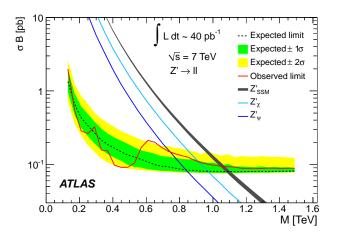


FIG. 5: Expected and observed 95% C.L. limits on  $\sigma B$  and expected  $\sigma B$  for  $Z'_{\rm SSM}$  production and the two  $E_6$ -motivated Z' models with lowest and highest  $\sigma B$  for the combination of the electron and muon channels. The thickness of the  $Z'_{\rm SSM}$  theory curve represents the theoretical uncertainty and holds for the other theory curves.

mass limit for the  $Z'_{\rm SSM}$  is 1.048 TeV (observed) and 1.088 TeV (expected). The combined mass limits on the  $E_6$ -motivated models are given in Table V. The limits on the  $E_6$ -motivated  $Z'_I$  and  $Z'_{\rm S}$  are 0.842 TeV and 0.871 TeV, more stringent than the previous highest limits [18].

Although the lepton decay angular distributions are not the same for Z' and  $Z^*$  bosons, we found the difference in geometrical acceptance to be negligible for boson pole masses above 750 GeV. The same procedure as for the Z' is used to calculate a limit on  $\sigma B(Z^* \to \ell^+\ell^-)$  and on the  $Z^*$  mass in each channel and for their com-

TABLE IV:  $e^+e^-, \, \mu^+\mu^-$  and combined 95% C.L. mass and  $\sigma B$  limits on  $Z'_{\rm SSM}$ .

	Observe	d limit	Expected limit		
	mass [TeV]	$\sigma B \text{ [pb]}$	mass [TeV]	$\sigma B \text{ [pb]}$	
$Z'_{\rm SSM} \to e^+e^-$	0.957	0.155	0.967	0.145	
$Z'_{\rm SSM} \to \mu^+ \mu^-$	0.834	0.297	0.900	0.201	
$Z'_{\rm SSM} \to \ell^+ \ell^-$	1.048	0.094	1.088	0.081	

TABLE V: Combined mass limits at 95% C.L. on the  $E_6$ -motivated Z' models.

Model	$Z_\psi'$	$Z_{ m N}'$	$Z'_{\eta}$	$Z_I'$	$Z_{ m S}'$	$Z_\chi'$
Mass limit [TeV]	0.738	0.763	0.771	0.842	0.871	0.900

TABLE VI:  $e^+e^-$ ,  $\mu^+\mu^-$  and combined 95% C.L. mass and  $\sigma B$  limits on  $Z^*$  production.

0	Observe		Expected limit		
	mass [TeV]	$\sigma B \text{ [pb]}$	mass [TeV	$\sigma B \text{ [pb]}$	
$Z^*  o e^+ e^-$	1.058	0.149	1.062	0.143	
$Z^* \to \mu^+ \mu^-$	0.946	0.265	0.995	0.199	
$Z^* \to \ell^+ \ell^-$	1.152	0.089	1.185	0.080	

bination. The results are displayed in Table VI. The combined mass limit for the  $Z^{\ast}$  boson is 1.152 TeV (observed) and 1.185 TeV (expected). This is the first direct limit on this particle.

In conclusion, the ATLAS detector has been used to search for narrow resonances in the invariant mass spectrum above 110 GeV of  $e^+e^-$  and  $\mu^+\mu^-$  final states with  $\sim 40~{\rm pb}^{-1}$  of proton-proton data. No evidence for such a resonance is found. Limits on the cross section times branching ratio  $\sigma B(Z' \to \ell^+\ell^-)$  are calculated, as well as mass limits on the  $Z'_{\rm SSM}$  (1.048 TeV), the  $Z^*$  (1.152 TeV) and  $E_6$ -motivated Z' bosons (in the range 0.738–0.900 TeV). For certain  $E_6$ -motivated models, these limits are more stringent than the corresponding limits from the Tevatron.

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## The ATLAS Collaboration

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G. Aad<sup>48</sup>, B. Abbott<sup>111</sup>, J. Abdallah<sup>11</sup>, A.A. Abdelalim<sup>49</sup>, A. Abdesselam<sup>118</sup>, O. Abdinov<sup>10</sup>, B. Abi<sup>112</sup>, M. Abolins<sup>88</sup>, H. Abramowicz<sup>153</sup>, H. Abreu<sup>115</sup>, E. Acerbi<sup>89a,89b</sup>, B.S. Acharya<sup>164a,164b</sup>, D.L. Adams<sup>24</sup>, T.N. Addy<sup>56</sup>, J. Adelman<sup>175</sup>, M. Aderholz<sup>99</sup>, S. Adomeit<sup>98</sup>, P. Adragna<sup>75</sup>, T. Adye<sup>129</sup>, S. Aefsky<sup>22</sup>, J.A. Aguilar-Saavedra<sup>124b,a</sup>, M. Aharrouche<sup>81</sup>, S.P. Ahlen<sup>21</sup>, F. Ahles<sup>48</sup>, A. Ahmad<sup>148</sup>, M. Ahsan<sup>40</sup>, G. Aielli<sup>133a,133b</sup>, T. Akdogan<sup>18a</sup>, T.P.A. Åkesson<sup>79</sup>, G. Akimoto<sup>155</sup>, A.V. Akimov <sup>94</sup>, A. Akiyama<sup>67</sup>, M.S. Alam<sup>1</sup>, M.A. Alam<sup>76</sup>, S. Albrand<sup>55</sup>, M. Aleksa<sup>29</sup>, I.N. Aleksandrov<sup>65</sup>, F. Alessandria<sup>89a</sup>, C. Alexa<sup>25a</sup>, G. Alexander<sup>153</sup>, G. Alexandre<sup>49</sup>, T. Alexopoulos<sup>9</sup>, M. Alhroob<sup>20</sup>, M. Aliev<sup>15</sup>, G. Alimonti<sup>89a</sup>, J. Alison<sup>120</sup>, M. Aliyev<sup>10</sup>, P.P. Allport<sup>73</sup>, S.E. Allwood-Spiers<sup>53</sup>, J. Almond<sup>82</sup>, A. Aloisio<sup>102a,102b</sup>, R. Alon<sup>171</sup>, A. Alonso<sup>79</sup>, M.G. Alviggi<sup>102a,102b</sup>, K. Amako<sup>66</sup>, P. Amaral<sup>29</sup>, C. Amelung<sup>22</sup>, V.V. Ammosov<sup>128</sup>, A. Amorim<sup>124a,b</sup>, G. Amorós<sup>167</sup>, N. Amram<sup>153</sup>, C. Anastopoulos<sup>139</sup>, T. Andeen<sup>34</sup>, C.F. Anders<sup>20</sup>, K.J. Anderson<sup>30</sup>, A. Andreazza<sup>89a,89b</sup>, V. Andrei<sup>58a</sup>, M-L. Andrieux<sup>55</sup>, X.S. Anduaga<sup>70</sup>, A. Angerami<sup>34</sup>, F. Anghinolfi<sup>29</sup>, N. Anios<sup>124a</sup>, A. Annovi<sup>47</sup>, A. Antonaki<sup>8</sup>, M. Antonelli<sup>47</sup>, S. Antonelli<sup>19a,19b</sup>.
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    Y. Arai<sup>66</sup>, A.T.H. Arce<sup>44</sup>, J.P. Archambault<sup>28</sup>, S. Arfaoui<sup>29</sup>, c, J-F. Arguin<sup>14</sup>, E. Arik<sup>18a</sup>, M. Arik<sup>18a</sup>, A.J. Armbruster<sup>87</sup>, O. Arnaez<sup>81</sup>, C. Arnault<sup>115</sup>, A. Artamonov<sup>95</sup>, G. Artoni<sup>132a,132b</sup>, D. Arutinov<sup>20</sup>, S. Asai<sup>155</sup>, R. Asfandiyarov<sup>172</sup>, S. Ask<sup>27</sup>, B. Åsman<sup>146a,146b</sup>, L. Asquith<sup>5</sup>, K. Assamagan<sup>24</sup>, A. Astbury<sup>169</sup>, A. Astvatsatourov<sup>52</sup>, G. Atoian<sup>175</sup>, B. Aubert<sup>4</sup>, B. Auerbach<sup>175</sup>, E. Auge<sup>115</sup>, K. Augsten<sup>127</sup>, M. Aurousseau<sup>145a</sup>, N. Austin<sup>73</sup>, R. Avramidou<sup>9</sup>, D. Axen<sup>168</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>93,d</sup>, Y. Azuma<sup>155</sup>, M.A. Baak<sup>29</sup>, G. Baccaglioni<sup>89a</sup>, R. Avramidou<sup>9</sup>, D. Axen<sup>168</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>93,d</sup>, Y. Azuma<sup>155</sup>, M.A. Baak<sup>29</sup>, G. Baccaglioni<sup>89a</sup>, R. Ayramidou<sup>9</sup>, D. Axen<sup>168</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>93,d</sup>, Y. Azuma<sup>155</sup>, M.A. Baak<sup>29</sup>, G. Baccaglioni<sup>89a</sup>, R. Ayramidou<sup>9</sup>, D. Axen<sup>168</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>93,d</sup>, Y. Azuma<sup>155</sup>, M.A. Baak<sup>29</sup>, G. Baccaglioni<sup>89a</sup>, R. Ayramidou<sup>9</sup>, D. Axen<sup>168</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>93,d</sup>, Y. Azuma<sup>155</sup>, M.A. Baak<sup>29</sup>, G. Baccaglioni<sup>89a</sup>, R. Ayramidou<sup>9</sup>, D. Axen<sup>168</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>93,d</sup>, Y. Azuma<sup>155</sup>, M.A. Baak<sup>29</sup>, G. Baccaglioni<sup>89a</sup>, R. Ayramidou<sup>9</sup>, D. Axen<sup>168</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>93,d</sup>, Y. Azuma<sup>155</sup>, M.A. Baak<sup>29</sup>, G. Baccaglioni<sup>89a</sup>, R. Ayramidou<sup>9</sup>, A. A
  R. Avramidou<sup>5</sup>, D. Axen<sup>105</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>35,4</sup>, Y. Azuma<sup>155</sup>, M.A. Baak<sup>25</sup>, G. Baccaghoni<sup>534</sup>, C. Bacci<sup>134a,134b</sup>, A.M. Bach<sup>14</sup>, H. Bachacou<sup>136</sup>, K. Bachas<sup>29</sup>, G. Bachy<sup>29</sup>, M. Backes<sup>49</sup>, M. Backhaus<sup>20</sup>, E. Badescu<sup>25a</sup>, P. Bagnaia<sup>132a,132b</sup>, S. Bahinipati<sup>2</sup>, Y. Bai<sup>32a</sup>, D.C. Bailey<sup>158</sup>, T. Bain<sup>158</sup>, J.T. Baines<sup>129</sup>, O.K. Baker<sup>175</sup>, M.D. Baker<sup>24</sup>, S. Baker<sup>77</sup>, F. Baltasar Dos Santos Pedrosa<sup>29</sup>, E. Banas<sup>38</sup>, P. Banerjee<sup>93</sup>, Sw. Banerjee<sup>169</sup>, D. Banfi<sup>29</sup>, A. Bangert<sup>137</sup>, V. Bansal<sup>169</sup>, H.S. Bansil<sup>17</sup>, L. Barak<sup>171</sup>, S.P. Baranov<sup>94</sup>, A. Barashkou<sup>65</sup>, A. Barbaro Galtieri<sup>14</sup>, T. Barber<sup>27</sup>, E.L. Barberio<sup>86</sup>, D. Barberis<sup>50a,50b</sup>, M. Barbero<sup>20</sup>, D.Y. Bardin<sup>65</sup>, T. Barillari<sup>99</sup>, M. Barisonzi<sup>174</sup>, T. Barklow<sup>143</sup>, N. Barlow<sup>27</sup>, B.M. Barnett<sup>129</sup>, R.M. Barnett<sup>14</sup>,
D.Y. Bardin<sup>65</sup>, T. Barillari<sup>99</sup>, M. Barisonzi<sup>174</sup>, T. Barklow<sup>143</sup>, N. Barlow<sup>27</sup>, B.M. Barnett<sup>129</sup>, R.M. Barnett<sup>14</sup>, A. Baroncelli<sup>134a</sup>, A.J. Barr<sup>118</sup>, F. Barreiro<sup>80</sup>, J. Barreiro Guimarães da Costa<sup>57</sup>, P. Barrillon<sup>115</sup>, R. Bartoldus<sup>143</sup>, A.E. Barton<sup>71</sup>, D. Bartsch<sup>20</sup>, V. Bartsch<sup>149</sup>, R.L. Bates<sup>53</sup>, L. Batkova<sup>144a</sup>, J.R. Batley<sup>27</sup>, A. Battaglia<sup>16</sup>, M. Battistin<sup>29</sup>, G. Battistoni<sup>89a</sup>, F. Bauer<sup>136</sup>, H.S. Bawa<sup>143,e</sup>, B. Beare<sup>158</sup>, T. Beau<sup>78</sup>, P.H. Beauchemin<sup>118</sup>, R. Beccherle<sup>50a</sup>, P. Bechtle<sup>41</sup>, H.P. Beck<sup>16</sup>, M. Beckingham<sup>48</sup>, K.H. Becks<sup>174</sup>, A.J. Beddall<sup>18c</sup>, A. Beddall<sup>18c</sup>, S. Bedikian<sup>175</sup>, V.A. Bednyakov<sup>65</sup>, C.P. Bee<sup>83</sup>, M. Begel<sup>24</sup>, S. Behar Harpaz<sup>152</sup>, P.K. Behera<sup>63</sup>, M. Beimforde<sup>99</sup>, C. Belanger-Champagne<sup>166</sup>, P.J. Bell<sup>49</sup>, W.H. Bell<sup>49</sup>, G. Bella<sup>153</sup>, L. Bellagamba<sup>19a</sup>, F. Bellina<sup>29</sup>, M. Bellomo<sup>119a</sup>, A. Belloni<sup>57</sup>, O. Beloborodova<sup>107</sup>, K. Belotskiy<sup>96</sup>, O. Beltramello<sup>29</sup>, S. Ben Ami<sup>152</sup>, O. Benary<sup>153</sup>, D. Benchekroun<sup>135a</sup>, C. Benchouk<sup>83</sup>, M. Bendel<sup>81</sup>, B.H. Benedict<sup>163</sup>, N. Benekos<sup>165</sup>, Y. Benhammou<sup>153</sup>, D.P. Benjamin<sup>44</sup>, M. Benoit<sup>115</sup>, J.R. Bensinger<sup>22</sup>, K. Benslama<sup>130</sup>, S. Bentvelsen<sup>105</sup>, D. Berge<sup>29</sup>, E. Bergeaas Kuutmann<sup>41</sup>, N. Berger<sup>4</sup>, F. Berghaus<sup>169</sup>, E. Berglund<sup>49</sup>, J. Beringer<sup>14</sup>, K. Bernardet<sup>83</sup>, P. Bernat<sup>77</sup>, R. Bernhard<sup>48</sup>, C. Bernius<sup>24</sup>, T. Berry<sup>76</sup>, A. Bertin<sup>19a,19b</sup>, F. Bertinelli<sup>29</sup>, F. Bertolucci<sup>122a,122b</sup>, M.I. Besana<sup>89a,89b</sup>, N. Besson<sup>136</sup>, S. Bethke<sup>99</sup>, W. Bhimii<sup>45</sup>, R.M. Bianchi<sup>29</sup>, M. Bianco<sup>72a,72b</sup>, O. Biebel<sup>98</sup>, S.P. Bieniek<sup>77</sup>,
  R. Bernhard<sup>45</sup>, C. Bernius<sup>47</sup>, T. Berry<sup>10</sup>, A. Bertin<sup>104</sup>, F. Bertinelli<sup>27</sup>, F. Bertolucci<sup>1224</sup>, M.I. Besana<sup>034</sup>, S. N. Besson<sup>136</sup>, S. Bethke<sup>99</sup>, W. Bhimji<sup>45</sup>, R.M. Bianchi<sup>29</sup>, M. Bianco<sup>72a</sup>, 72b, O. Biebel<sup>98</sup>, S.P. Bieniek<sup>77</sup>, J. Biesiada<sup>14</sup>, M. Biglietti<sup>134a</sup>, 134b, H. Bilokon<sup>47</sup>, M. Bindi<sup>19a</sup>, 19b, S. Binet<sup>115</sup>, A. Bingul<sup>18c</sup>, C. Bini<sup>132a</sup>, 132b, C. Biscarat<sup>177</sup>, U. Bitenc<sup>48</sup>, K.M. Black<sup>21</sup>, R.E. Blair<sup>5</sup>, J.-B. Blanchard<sup>115</sup>, G. Blanchot<sup>29</sup>, C. Blocker<sup>22</sup>, J. Blocki<sup>38</sup>, A. Blondel<sup>49</sup>, W. Blum<sup>81</sup>, U. Blumenschein<sup>54</sup>, G.J. Bobbink<sup>105</sup>, V.B. Bobrovnikov<sup>107</sup>, S.S. Bocchetta<sup>79</sup>, A. Bocci<sup>44</sup>, C.R. Boddy<sup>118</sup>, M. Boehler<sup>41</sup>, J. Boek<sup>174</sup>, N. Boelaert<sup>35</sup>, S. Böser<sup>77</sup>, J.A. Bogaerts<sup>29</sup>, A. Bogdanchikov<sup>107</sup>, A. Bogouch<sup>90</sup>, C. Bohm<sup>146a</sup>, V. Boisvert<sup>76</sup>, T. Bold<sup>163</sup>, V. Boldea<sup>25a</sup>, N.M. Bolnet<sup>136</sup>, M. Bona<sup>75</sup>, M. Bona<sup>75</sup>, D. Bold<sup>163</sup>, P. Bold<sup>139</sup>, R. Bold<sup>139</sup>, R. Bold<sup>163</sup>, R. Bold<sup>16</sup>
        V.G. Bondarenko<sup>96</sup>, M. Boonekamp<sup>136</sup>, G. Boorman<sup>76</sup>, C.N. Booth<sup>139</sup>, P. Booth<sup>139</sup>, S. Bordoni<sup>78</sup>, C. Borer<sup>16</sup>,
      A. Borisov<sup>128</sup>, G. Borissov<sup>71</sup>, I. Borjanovic<sup>12a</sup>, S. Borroni<sup>132a,132b</sup>, K. Bos<sup>105</sup>, D. Boscherini<sup>19a</sup>, M. Bosman<sup>11</sup>,
    H. Boterenbrood<sup>105</sup>, D. Botterill<sup>129</sup>, J. Bouchami<sup>93</sup>, J. Boudreau<sup>123</sup>, E.V. Bouhova-Thacker<sup>71</sup>, C. Boulahouache<sup>123</sup>, C. Bourdarios<sup>115</sup>, N. Bousson<sup>83</sup>, A. Boveia<sup>30</sup>, J. Boyd<sup>29</sup>, I.R. Boyko<sup>65</sup>, N.I. Bozhko<sup>128</sup>, I. Bozovic-Jelisavcic<sup>12b</sup>, J. Bracinik<sup>17</sup>, A. Braem<sup>29</sup>, P. Branchini<sup>134a</sup>, G.W. Brandenburg<sup>57</sup>, A. Brandt<sup>7</sup>, G. Brandt<sup>15</sup>, O. Brandt<sup>54</sup>, U. Bratzler<sup>156</sup>, B. Brau<sup>84</sup>, J.E. Brau<sup>114</sup>, H.M. Braun<sup>174</sup>, B. Brelier<sup>158</sup>, J. Bremer<sup>29</sup>, R. Brenner<sup>166</sup>, S. Bressler<sup>152</sup>, D. Breton<sup>115</sup>, N.D. Brett<sup>118</sup>, D. Britton<sup>53</sup>, F.M. Brochu<sup>27</sup>, I. Brock<sup>20</sup>, R. Brock<sup>88</sup>, T.J. Brodbeck<sup>71</sup>, E. Brodet<sup>153</sup>,
      F. Broggi<sup>89a</sup>, C. Bromberg<sup>88</sup>, G. Brooijmans<sup>34</sup>, W.K. Brooks<sup>31b</sup>, G. Brown<sup>82</sup>, E. Brubaker<sup>30</sup>, P.A. Bruckman de Renstrom<sup>38</sup>, D. Bruncko<sup>144b</sup>, R. Bruneliere<sup>48</sup>, S. Brunet<sup>61</sup>, A. Bruni<sup>19a</sup>, G. Bruni<sup>19a</sup>,
  P.A. Bruckman de Renstrom<sup>56</sup>, D. Bruncko<sup>1445</sup>, R. Bruneliere<sup>46</sup>, S. Brunet<sup>61</sup>, A. Bruni<sup>19a</sup>, G. Bruni<sup>19a</sup>, M. Bruschi<sup>19a</sup>, T. Buanes<sup>13</sup>, F. Bucci<sup>49</sup>, J. Buchanan<sup>118</sup>, N.J. Buchanan<sup>2</sup>, P. Buchholz<sup>141</sup>, R.M. Buckingham<sup>118</sup>, A.G. Buckley<sup>45</sup>, S.I. Buda<sup>25a</sup>, I.A. Budagov<sup>65</sup>, B. Budick<sup>108</sup>, V. Büscher<sup>81</sup>, L. Bugge<sup>117</sup>, D. Buira-Clark<sup>118</sup>, E.J. Buisi<sup>105</sup>, O. Bulekov<sup>96</sup>, M. Bunse<sup>42</sup>, T. Buran<sup>117</sup>, H. Burckhart<sup>29</sup>, S. Burdin<sup>73</sup>, T. Burgess<sup>13</sup>, S. Burke<sup>129</sup>, E. Busato<sup>33</sup>, P. Bussey<sup>53</sup>, C.P. Buszello<sup>166</sup>, F. Butin<sup>29</sup>, B. Butler<sup>143</sup>, J.M. Butler<sup>21</sup>, C.M. Buttar<sup>53</sup>, J.M. Butterworth<sup>77</sup>, W. Buttinger<sup>27</sup>, T. Byatt<sup>77</sup>, S. Cabrera Urbán<sup>167</sup>, D. Caforio<sup>19a,19b</sup>, O. Cakir<sup>3a</sup>, P. Calafiura<sup>14</sup>, G. Calderini<sup>78</sup>, P. Calfayan<sup>98</sup>, R. Calkins<sup>106</sup>, L.P. Caloba<sup>23a</sup>, R. Caloi<sup>132a,132b</sup>, D. Calvet<sup>33</sup>, S. Calvet<sup>33</sup>, R. Camacho Toro<sup>33</sup>, A. Camard<sup>78</sup>, P. Camarri<sup>133a,133b</sup>, M. Cambiaghi<sup>119a,119b</sup>, D. Cameron<sup>117</sup>, J. Cammin<sup>20</sup>,
```

```
S. Campana<sup>29</sup>, M. Campanelli<sup>77</sup>, V. Canale<sup>102a,102b</sup>, F. Canelli<sup>30</sup>, A. Canepa<sup>159a</sup>, J. Cantero<sup>80</sup>, L. Capasso<sup>102a,102b</sup>,
   M.D.M. Capeans Garrido<sup>29</sup>, I. Caprini<sup>25a</sup>, M. Caprini<sup>25a</sup>, D. Capriotti<sup>99</sup>, M. Capua<sup>36a,36b</sup>, R. Caputo<sup>148</sup>,
   C. Caramarcu<sup>25a</sup>, R. Cardarelli<sup>133a</sup>, T. Carli<sup>29</sup>, G. Carlino<sup>102a</sup>, L. Carminati<sup>89a,89b</sup>, B. Caron<sup>159a</sup>, S. Caron<sup>48</sup>, C. Carpentieri<sup>48</sup>, G.D. Carrillo Montoya<sup>172</sup>, A.A. Carter<sup>75</sup>, J.R. Carter<sup>27</sup>, J. Carvalho<sup>124a,g</sup>, D. Casadei<sup>108</sup>,
 M.P. Casado<sup>11</sup>, M. Cascella<sup>122a,122b</sup>, C. Caso<sup>50a,50b,*</sup>, A.M. Castaneda Hernandez<sup>172</sup>, E. Castaneda-Miranda<sup>172</sup>, V. Castillo Gimenez<sup>167</sup>, N.F. Castro<sup>124a</sup>, G. Cataldi<sup>72a</sup>, F. Cataneo<sup>29</sup>, A. Catinaccio<sup>29</sup>, J.R. Catmore<sup>71</sup>, A. Cattai<sup>29</sup>, G. Cattani<sup>133a,133b</sup>, S. Caughron<sup>88</sup>, D. Cauz<sup>164a,164c</sup>, A. Cavallari<sup>132a,132b</sup>, P. Cavalleri<sup>78</sup>, D. Cavalli<sup>89a</sup>, M. Cavalli-Sforza<sup>11</sup>, V. Cavasinni<sup>122a,122b</sup>, A. Cazzato<sup>72a,72b</sup>, F. Ceradini<sup>134a,134b</sup>, A.S. Cerqueira<sup>23a</sup>, A. Cerri<sup>29</sup>,
   L. Cerrito<sup>75</sup>, F. Cerutti<sup>47</sup>, S.A. Cetin<sup>18b</sup>, F. Cevenini<sup>102a,102b</sup>, A. Chafaq<sup>135a</sup>, D. Chakraborty<sup>106</sup>, K. Chan<sup>2</sup>,
B. Chapleau<sup>85</sup>, J.D. Chapman<sup>27</sup>, J.W. Chapman<sup>87</sup>, E. Chareyre<sup>78</sup>, D.G. Charlton<sup>17</sup>, V. Chavda<sup>82</sup>, S. Cheatham<sup>71</sup>, S. Chekanov<sup>5</sup>, S.V. Chekulaev<sup>159a</sup>, G.A. Chelkov<sup>65</sup>, M.A. Chelstowska<sup>104</sup>, C. Chen<sup>64</sup>, H. Chen<sup>24</sup>, L. Chen<sup>2</sup>, S. Chen<sup>32c</sup>, T. Chen<sup>32c</sup>, X. Chen<sup>172</sup>, S. Cheng<sup>32a</sup>, A. Cheplakov<sup>65</sup>, V.F. Chepurnov<sup>65</sup>, R. Cherkaoui El Moursli<sup>135e</sup>, V. Chernyatin<sup>24</sup>, E. Cheu<sup>6</sup>, S.L. Cheung<sup>158</sup>, L. Chevalier<sup>136</sup>, G. Chiefari<sup>102a,102b</sup>, L. Chikovani<sup>51</sup>, J.T. Childers<sup>58a</sup>,
   A. Chilingarov<sup>71</sup>, G. Chiodini<sup>72a</sup>, M.V. Chizhov<sup>65</sup>, G. Choudalakis<sup>30</sup>, S. Chouridou<sup>137</sup>, I.A. Christidi<sup>77</sup>, A. Christov<sup>48</sup>, D. Chromek-Burckhart<sup>29</sup>, M.L. Chu<sup>151</sup>, J. Chudoba<sup>125</sup>, G. Ciapetti<sup>132a,132b</sup>, K. Ciba<sup>37</sup>, A.K. Ciftci<sup>3a</sup>,
A. Christov -, D. Chromek-Burcknart -, M.L. Chu<sup>151</sup>, J. Chudoba<sup>123</sup>, G. Chapetth<sup>1524</sup>, 1325, K. Ciba<sup>37</sup>, A.K. Cil R. Ciftci<sup>3a</sup>, D. Cinca<sup>33</sup>, V. Cindro<sup>74</sup>, M.D. Ciobotaru<sup>163</sup>, C. Ciocca<sup>19a,19b</sup>, A. Ciocio<sup>14</sup>, M. Cirilli<sup>87</sup>, M. Ciubancan<sup>25a</sup>, A. Clark<sup>49</sup>, P.J. Clark<sup>45</sup>, W. Cleland<sup>123</sup>, J.C. Clemens<sup>83</sup>, B. Clement<sup>55</sup>, C. Clement<sup>146a,146b</sup>, R.W. Clifft<sup>129</sup>, Y. Coadou<sup>83</sup>, M. Cobal<sup>164a,164c</sup>, A. Coccaro<sup>50a,50b</sup>, J. Cochran<sup>64</sup>, P. Coe<sup>118</sup>, J.G. Cogan<sup>143</sup>, J. Coggeshall<sup>165</sup>, E. Cogneras<sup>177</sup>, C.D. Cojocaru<sup>28</sup>, J. Colas<sup>4</sup>, A.P. Colijn<sup>105</sup>, C. Collard<sup>115</sup>, N.J. Collins<sup>17</sup>, C. Colling <sup>175</sup>, C. Co
  C. Collins-Tooth<sup>53</sup>, J. Collot<sup>55</sup>, G. Colon<sup>84</sup>, G. Comune<sup>88</sup>, P. Conde Muiño<sup>124a</sup>, E. Coniavitis<sup>118</sup>, M.C. Conidi<sup>11</sup>, M. Consonni<sup>104</sup>, S. Constantinescu<sup>25a</sup>, C. Conta<sup>119a,119b</sup>, F. Conventi<sup>102a,h</sup>, J. Cook<sup>29</sup>, M. Cooke<sup>14</sup>, B.D. Cooper<sup>77</sup>,
  A.M. Cooper-Sarkar<sup>118</sup>, N.J. Cooper-Smith<sup>76</sup>, K. Copic<sup>34</sup>, T. Cornelissen<sup>50a,50b</sup>, M. Corradi<sup>19a</sup>, F. Corriveau<sup>85,i</sup>,
 A. Cortes-Gonzalez<sup>165</sup>, G. Cortiana<sup>99</sup>, G. Costa<sup>89a</sup>, M.J. Costa<sup>167</sup>, D. Costanzo<sup>139</sup>, T. Costin<sup>30</sup>, D. Côté<sup>29</sup>, R. Coura Torres<sup>23a</sup>, L. Courneyea<sup>169</sup>, G. Cowan<sup>76</sup>, C. Cowden<sup>27</sup>, B.E. Cox<sup>82</sup>, K. Cranmer<sup>108</sup>, F. Crescioli<sup>122a,122b</sup>, M. Cristinziani<sup>20</sup>, G. Crosetti<sup>36a,36b</sup>, R. Crupi<sup>72a,72b</sup>, S. Crépé-Renaudin<sup>55</sup>, C. Cuenca Almenar<sup>175</sup>, T. Cuhadar Donszelmann<sup>139</sup>, S. Cuneo<sup>50a,50b</sup>, M. Curatolo<sup>47</sup>, C.J. Curtis<sup>17</sup>, P. Cwetanski<sup>61</sup>, H. Czirr<sup>141</sup>,
  Z. Czyczula<sup>117</sup>, S. D'Auria<sup>53</sup>, M. D'Onofrio<sup>73</sup>, A. D'Orazio<sup>132a,132b</sup>, A. Da Rocha Gesualdi Mello<sup>23a</sup>.
   P.V.M. Da Silva<sup>23a</sup>, C. Da Via<sup>82</sup>, W. Dabrowski<sup>37</sup>, A. Dahlhoff<sup>48</sup>, T. Dai<sup>87</sup>, C. Dallapiccola<sup>84</sup>, S.J. Dallison<sup>129,*</sup>,
 M. Dam<sup>35</sup>, M. Dameri<sup>50a,50b</sup>, D.S. Damiani<sup>137</sup>, H.O. Danielsson<sup>29</sup>, R. Dankers<sup>105</sup>, D. Dannheim<sup>99</sup>, V. Dao<sup>49</sup>, G. Darbo<sup>50a</sup>, G.L. Darlea<sup>25b</sup>, C. Daum<sup>105</sup>, J.P. Dauvergne <sup>29</sup>, W. Davey<sup>86</sup>, T. Davidek<sup>126</sup>, N. Davidson<sup>86</sup>, R. Davidson<sup>71</sup>, M. Davies<sup>93</sup>, A.R. Davison<sup>77</sup>, E. Dawe<sup>142</sup>, I. Dawson<sup>139</sup>, J.W. Dawson<sup>5,*</sup>, R.K. Daya<sup>39</sup>, K. De<sup>7</sup>,
   R. de Asmundis<sup>102a</sup>, S. De Castro<sup>19a,19b</sup>, P.E. De Castro Faria Salgado<sup>24</sup>, S. De Cecco<sup>78</sup>, J. de Graat<sup>98</sup>.
  N. De Groot<sup>104</sup>, P. de Jong<sup>105</sup>, C. De La Taille<sup>115</sup>, H. De la Torre<sup>80</sup>, B. De Lotto<sup>164a,164c</sup>, L. De Mora<sup>71</sup>,
 L. De Nooij<sup>105</sup>, M. De Oliveira Branco<sup>29</sup>, D. De Pedis<sup>132a</sup>, P. de Saintignon<sup>55</sup>, A. De Salvo<sup>132a</sup>, U. De Sanctis<sup>164a,164c</sup>, A. De Santo<sup>149</sup>, J.B. De Vivie De Regie<sup>115</sup>, S. Dean<sup>77</sup>, D.V. Dedovich<sup>65</sup>, J. Degenhardt<sup>120</sup>, M. Dehchar<sup>118</sup>, M. Deile<sup>98</sup>, C. Del Papa<sup>164a,164c</sup>, J. Del Peso<sup>80</sup>, T. Del Prete<sup>122a,122b</sup>, A. Dell'Acqua<sup>29</sup>, L. Dell'Asta<sup>89a,89b</sup>, M. Della Pietra<sup>102a,h</sup>, D. della Volpe<sup>102a,102b</sup>, M. Delmastro<sup>29</sup>, P. Delpierre<sup>83</sup>, N. Delruelle<sup>29</sup>,
  P.A. Delsart<sup>55</sup>, C. Deluca<sup>148</sup>, S. Demers<sup>175</sup>, M. Demichev<sup>65</sup>, B. Demirkoz<sup>11</sup>, J. Deng<sup>163</sup>, S.P. Denisov<sup>128</sup>,
   D. Derendarz<sup>38</sup>, J.E. Derkaoui<sup>135d</sup>, F. Derue<sup>78</sup>, P. Dervan<sup>73</sup>, K. Desch<sup>20</sup>, E. Devetak<sup>148</sup>, P.O. Deviveiros<sup>158</sup>,
 D. Derendarz<sup>30</sup>, J.E. Derkaoui<sup>1004</sup>, F. Derue<sup>10</sup>, P. Dervan<sup>10</sup>, K. Desch<sup>20</sup>, E. Devetak<sup>110</sup>, P.O. Deviveiros<sup>100</sup>, A. Dewhurst<sup>129</sup>, B. DeWilde<sup>148</sup>, S. Dhaliwal<sup>158</sup>, R. Dhullipudi<sup>24</sup>, A. Di Ciaccio<sup>133a,133b</sup>, L. Di Ciaccio<sup>4</sup>, A. Di Girolamo<sup>29</sup>, B. Di Girolamo<sup>29</sup>, S. Di Luise<sup>134a,134b</sup>, A. Di Mattia<sup>88</sup>, B. Di Micco<sup>29</sup>, R. Di Nardo<sup>133a,133b</sup>, A. Di Simone<sup>133a,133b</sup>, R. Di Sipio<sup>19a,19b</sup>, M.A. Diaz<sup>31a</sup>, F. Diblen<sup>18c</sup>, E.B. Diehl<sup>87</sup>, H. Dietl<sup>99</sup>, J. Dietrich<sup>48</sup>, T.A. Dietzsch<sup>58a</sup>, S. Diglio<sup>115</sup>, K. Dindar Yagci<sup>39</sup>, J. Dingfelder<sup>20</sup>, C. Dionisi<sup>132a,132b</sup>, P. Dita<sup>25a</sup>, S. Dita<sup>25a</sup>, P. Dita<sup>25a</sup>, S. Dita<sup>25a</sup>, S. Dita<sup>25a</sup>, S. Dita<sup>25a</sup>, P. Dita<sup>25a</sup>, S. Di
 F. Dittus<sup>29</sup>, F. Djama<sup>83</sup>, R. Djilkibaev<sup>108</sup>, T. Djobava<sup>51</sup>, M.A.B. do Vale<sup>23a</sup>, A. Do Valle Wemans<sup>124a</sup>, T.K.O. Doan<sup>4</sup>, M. Dobbs<sup>85</sup>, R. Dobinson <sup>29,*</sup>, D. Dobos<sup>42</sup>, E. Dobson<sup>29</sup>, M. Dobson<sup>163</sup>, J. Dodd<sup>34</sup>, O.B. Dogan<sup>18a,*</sup>, C. Doglioni<sup>118</sup>, T. Doherty<sup>53</sup>, Y. Doi<sup>66,*</sup>, J. Dolejsi<sup>126</sup>, I. Dolecc<sup>74</sup>, Z. Dolezal<sup>126</sup>, B.A. Dolgoshein<sup>96,*</sup>
 T. Dohmae<sup>155</sup>, M. Donadelli<sup>23b</sup>, M. Donega<sup>120</sup>, J. Donini<sup>55</sup>, J. Dopke<sup>29</sup>, A. Doria<sup>102a</sup>, A. Dos Anjos<sup>172</sup>, M. Dosil<sup>11</sup>, A. Dotti<sup>122a,122b</sup>, M.T. Dova<sup>70</sup>, J.D. Dowell<sup>17</sup>, A.D. Doxiadis<sup>105</sup>, A.T. Doyle<sup>53</sup>, Z. Drasal<sup>126</sup>, J. Drees<sup>174</sup>, N. Dressnandt<sup>120</sup>, H. Drevermann<sup>29</sup>, C. Driouichi<sup>35</sup>, M. Dris<sup>9</sup>, J.G. Drohan<sup>77</sup>, J. Dubbert<sup>99</sup>, T. Dubbs<sup>137</sup>,
   S. Dube<sup>14</sup>, E. Duchovni<sup>171</sup>, G. Duckeck<sup>98</sup>, A. Dudarev<sup>29</sup>, F. Dudziak<sup>64</sup>, M. Dührssen <sup>29</sup>, I.P. Duerdoth<sup>82</sup>,
L. Duflot<sup>115</sup>, M-A. Dufour<sup>85</sup>, M. Dunford<sup>29</sup>, H. Duran Yildiz<sup>3b</sup>, R. Duxfield<sup>139</sup>, M. Dwuznik<sup>37</sup>, F. Dydak<sup>29</sup>, D. Dzahini<sup>55</sup>, M. Düren<sup>52</sup>, W.L. Ebenstein<sup>44</sup>, J. Ebke<sup>98</sup>, S. Eckert<sup>48</sup>, S. Eckweiler<sup>81</sup>, K. Edmonds<sup>81</sup>, C.A. Edwards<sup>76</sup>, W. Ehrenfeld<sup>41</sup>, T. Ehrich<sup>99</sup>, T. Eifert<sup>29</sup>, G. Eigen<sup>13</sup>, K. Einsweiler<sup>14</sup>, E. Eisenhandler<sup>75</sup>, T. Ekelof<sup>166</sup>, M. El Kacimi<sup>4</sup>, M. Ellert<sup>166</sup>, S. Elles<sup>4</sup>, F. Ellinghaus<sup>81</sup>, K. Ellis<sup>75</sup>, N. Ellis<sup>29</sup>, J. Elmsheuser<sup>98</sup>, M. Elsing<sup>29</sup>, R. Ely<sup>14</sup>, D. Emeliyanov<sup>129</sup>, R. Engelmann<sup>148</sup>, A. Engl<sup>98</sup>, B. Epp<sup>62</sup>, A. Eppig<sup>87</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Epp<sup>62</sup>, A. Eppig<sup>87</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Epp<sup>63</sup>, A. Eppig<sup>87</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Epp<sup>64</sup>, A. Eppig<sup>87</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Epp<sup>65</sup>, A. Eppig<sup>87</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Epp<sup>68</sup>, A. Eppig<sup>88</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Epp<sup>68</sup>, A. Eppig<sup>88</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Eppig<sup>88</sup>, B. Eppig<sup>88</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Eppig<sup>88</sup>, B. Eppig<sup>88</sup>, B. Eppig<sup>88</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Eppig<sup>88</sup>, B. Eppig<sup>88</sup>, B. Eppig<sup>88</sup>, J. Erdmann<sup>54</sup>, A. Engl<sup>98</sup>, B. Eppig<sup>88</sup>, B. Eppig<sup></sup>
   A. Ereditato<sup>16</sup>, D. Eriksson<sup>146a</sup>, J. Ernst<sup>1</sup>, M. Ernst<sup>24</sup>, J. Ernwein<sup>136</sup>, D. Errede<sup>165</sup>, S. Errede<sup>165</sup>, E. Ertel<sup>81</sup>,
   M. Escalier<sup>115</sup>, C. Escobar<sup>167</sup>, X. Espinal Curull<sup>11</sup>, B. Esposito<sup>47</sup>, F. Etienne<sup>83</sup>, A.I. Etienvre<sup>136</sup>, E. Etzion<sup>153</sup>.
```

D. Evangelakou<sup>54</sup>, H. Evans<sup>61</sup>, L. Fabbri<sup>19a,19b</sup>, C. Fabre<sup>29</sup>, K. Facius<sup>35</sup>, R.M. Fakhrutdinov<sup>128</sup>, S. Falciano<sup>132a</sup>,

A.C. Falou<sup>115</sup>, Y. Fang<sup>172</sup>, M. Fanti<sup>89a,89b</sup>, A. Farbin<sup>7</sup>, A. Farilla<sup>134a</sup>, J. Farley<sup>148</sup>, T. Farooque<sup>158</sup>, S.M. Farrington<sup>118</sup>, P. Farthouat<sup>29</sup>, D. Fasching<sup>172</sup>, P. Fassnacht<sup>29</sup>, D. Fassouliotis<sup>8</sup>, B. Fatholahzadeh<sup>158</sup>, A. Favareto<sup>89a,89b</sup>, L. Fayard<sup>115</sup>, S. Fazio<sup>36a,36b</sup>, R. Febbraro<sup>33</sup>, P. Federic<sup>144a</sup>, O.L. Fedin<sup>121</sup>, I. Fedorko<sup>29</sup>, A. Favareto A. Fayard C. Fayard C. Fazio B. R. Febbraro R. Febbraro R. Federic A. P. Federic A. P. Federic Parado P. F. Federic Parado P. F. Fischer P. Fischer P. F. Fischer P. Fischer T. Flick<sup>174</sup>, L.R. Flores Castillo<sup>172</sup>, M.J. Flowerdew<sup>99</sup>, F. Föhlisch<sup>58a</sup>, M. Fokitis<sup>9</sup>, T. Fonseca Martin<sup>16</sup>, D.A. Forbush<sup>138</sup>, A. Formica<sup>136</sup>, A. Forti<sup>82</sup>, D. Fortin<sup>159a</sup>, J.M. Foster<sup>82</sup>, D. Foursier<sup>115</sup>, A. Foussat<sup>29</sup>, A.J. Fowler<sup>44</sup>, K. Fowler<sup>137</sup>, H. Fox<sup>71</sup>, P. Francavilla<sup>122a,122b</sup>, S. Franchino<sup>119a,119b</sup>, D. Francis<sup>29</sup>, T. Frank<sup>171</sup>, M. Franklin<sup>57</sup>, S. Franz<sup>29</sup>, M. Fraternali<sup>119a,119b</sup>, S. Fratina<sup>120</sup>, S.T. French<sup>27</sup>, R. Froeschl<sup>29</sup>, D. Froidevaux<sup>29</sup>, J.A. Frost<sup>27</sup>, C. Fukunaga<sup>156</sup>, E. Fullana Torregrosa<sup>29</sup>, J. Fuster<sup>167</sup>, C. Gabaldon<sup>29</sup>, O. Gabizon<sup>171</sup>, T. Gadfort<sup>24</sup>, S. Gadomski<sup>49</sup>, G. Gagliardi<sup>50a,50b</sup>, P. Gagnon<sup>61</sup>, C. Galea<sup>98</sup>, E.J. Gallas<sup>118</sup>, M.V. Gallas<sup>29</sup>, V. Gallo<sup>16</sup>, B.J. Gallop<sup>129</sup>, P. Gallus<sup>125</sup>, E. Galyaev<sup>40</sup>, K.K. Gan<sup>109</sup>, Y.S. Gao<sup>143</sup>, V.A. Gapienko<sup>128</sup>, A. Gaponenko<sup>14</sup>, B.J. Gallop<sup>129</sup>, P. Gallus<sup>123</sup>, E. Galyaev<sup>40</sup>, K.K. Gan<sup>109</sup>, Y.S. Gao<sup>143</sup>, V.A. Gapienko<sup>128</sup>, A. Gaponenko<sup>14</sup>, F. Garberson<sup>175</sup>, M. Garcia-Sciveres<sup>14</sup>, C. García<sup>167</sup>, J.E. García Navarro<sup>49</sup>, R.W. Gardner<sup>30</sup>, N. Garelli<sup>29</sup>, H. Garitaonandia<sup>105</sup>, V. Garonne<sup>29</sup>, J. Garvey<sup>17</sup>, C. Gatti<sup>47</sup>, G. Gaudio<sup>119a</sup>, O. Gaumer<sup>49</sup>, B. Gaur<sup>141</sup>, L. Gauthier<sup>136</sup>, I.L. Gavrilenko<sup>94</sup>, C. Gay<sup>168</sup>, G. Gaycken<sup>20</sup>, J-C. Gayde<sup>29</sup>, E.N. Gazis<sup>9</sup>, P. Ge<sup>32d</sup>, C.N.P. Gee<sup>129</sup>, D.A.A. Geerts<sup>105</sup>, Ch. Geich-Gimbel<sup>20</sup>, K. Gellerstedt<sup>146a,146b</sup>, C. Gemmel<sup>50a</sup>, A. Gemmel<sup>53</sup>, M.H. Genest<sup>98</sup>, S. Gentile<sup>132a,132b</sup>, M. George<sup>54</sup>, S. George<sup>76</sup>, P. Gerlach<sup>174</sup>, A. Gershon<sup>153</sup>, C. Geweniger<sup>58a</sup>, H. Ghazlane<sup>135b</sup>, P. Ghez<sup>4</sup>, N. Ghodbane<sup>33</sup>, B. Giacobbe<sup>19a</sup>, S. Giagu<sup>132a,132b</sup>, V. Giakoumopoulou<sup>8</sup>, V. Giangiobbe<sup>122a,122b</sup>, P. Ghez<sup>4</sup>, N. Ghodbane<sup>33</sup>, B. Giacobbe<sup>19a</sup>, S. Giagu<sup>132a,132b</sup>, V. Giakoumopoulou<sup>5</sup>, V. Giangiobbe<sup>122a,122b</sup>, F. Gianotti<sup>29</sup>, B. Gibbard<sup>24</sup>, A. Gibson<sup>158</sup>, S.M. Gibson<sup>29</sup>, G.F. Gieraltowski<sup>5</sup>, L.M. Gilbert<sup>118</sup>, M. Gilchriese<sup>14</sup>, V. Gilewsky<sup>91</sup>, D. Gillberg<sup>28</sup>, A.R. Gillman<sup>129</sup>, D.M. Gingrich<sup>2,d</sup>, J. Ginzburg<sup>153</sup>, N. Giokaris<sup>8</sup>, R. Giordano<sup>102a,102b</sup>, F.M. Giorgi<sup>15</sup>, P. Giovannini<sup>99</sup>, P.F. Giraud<sup>136</sup>, D. Giugni<sup>89a</sup>, P. Giusti<sup>19a</sup>, B.K. Gjelsten<sup>117</sup>, L.K. Gladilin<sup>97</sup>, C. Glasman<sup>80</sup>, J. Glatzer<sup>48</sup>, A. Glazov<sup>41</sup>, K.W. Glitza<sup>174</sup>, G.L. Glonti<sup>65</sup>, J. Godfrey<sup>142</sup>, J. Godlewski<sup>29</sup>, M. Goebel<sup>41</sup>, T. Göpfert<sup>43</sup>, C. Goeringer<sup>81</sup>, C. Gössling<sup>42</sup>, T. Göttfert<sup>99</sup>, S. Goldfarb<sup>87</sup>, D. Goldin<sup>39</sup>, T. Golling<sup>175</sup>, S.N. Golovnia<sup>128</sup>, A. Gomes<sup>124a,b</sup>, L.S. Gomez Fajardo<sup>41</sup>, R. Gonçalo<sup>76</sup>, J. Goncalves Pinto Firmino Da Costa<sup>41</sup>, L. Gonella<sup>20</sup>, A. Gonidec<sup>29</sup>, S. Gonzalez<sup>172</sup>, S. González de la Hoz<sup>167</sup>, M.L. Gonzalez Silva<sup>26</sup>, S. Gonzalez-Sevilla<sup>49</sup>, J.J. Goodson<sup>148</sup>, L. Goossens<sup>29</sup>, P.A. Gorbounov<sup>95</sup>, H.A. Gordon<sup>24</sup>, I. Gorelov<sup>103</sup>, G. Gorfine<sup>174</sup>, B. Gorini<sup>29</sup>, E. Gorini<sup>72a,72b</sup>, A. Gorišek<sup>74</sup>, E. Gornicki<sup>38</sup>, S.A. Gorokhov<sup>128</sup>, V.N. Goryachev<sup>128</sup>, B. Gosdzik<sup>41</sup>, M. Gosselink<sup>105</sup>, M. Goushèri<sup>65</sup>. M. Gouanère<sup>4</sup>. I. Gough Eschrich<sup>163</sup>. M. Gouighri<sup>135a</sup>. D. Goujdami<sup>135c</sup>, M.P. Goulette<sup>49</sup>, M.I. Gostkin<sup>65</sup>, M. Gouanère<sup>4</sup>, I. Gough Eschrich<sup>163</sup>, M. Gouighri<sup>135a</sup>, D. Goujdami<sup>135c</sup>, M.P. Goulette<sup>49</sup>, A.G. Goussiou<sup>138</sup>, C. Goy<sup>4</sup>, I. Grabowska-Bold<sup>163</sup>, V. Grabski<sup>176</sup>, P. Grafström<sup>29</sup>, C. Grah<sup>174</sup>, K-J. Grahn<sup>147</sup>, F. Grancagnolo<sup>72a</sup>, S. Grancagnolo<sup>15</sup>, V. Grassi<sup>148</sup>, V. Gratchev<sup>121</sup>, N. Grau<sup>34</sup>, H.M. Gray<sup>29</sup>, J.A. Gray<sup>148</sup>, E. Graziani<sup>134a</sup>, O.G. Grebenyuk<sup>121</sup>, D. Greenfield<sup>129</sup>, T. Greenshaw<sup>73</sup>, Z.D. Greenwood<sup>24,j</sup>, I.M. Gregor<sup>41</sup>, P. Greenier<sup>143</sup>, E. Griesmayer<sup>46</sup>, J. Griffiths<sup>138</sup>, N. Grigalashvili<sup>65</sup>, A.A. Grillo<sup>137</sup>, S. Grinstein<sup>11</sup>, P.L.Y. Gris<sup>33</sup>, Y.V. Grishkevich<sup>97</sup>, J.-F. Grivaz<sup>115</sup>, J. Grognuz<sup>29</sup>, M. Groh<sup>99</sup>, E. Gross<sup>171</sup>, J. Grosse-Knetter<sup>54</sup>, J. Groth-Jensen<sup>79</sup>, M. Gruwe<sup>29</sup>, K. Grybel<sup>141</sup>, V.J. Guarino<sup>5</sup>, D. Guest<sup>175</sup>, C. Guicheney<sup>33</sup>, A. Guida<sup>72a,72b</sup>, T. Guillemin<sup>4</sup>, S. Guindon<sup>54</sup>, H. Guler<sup>85,k</sup>, J. Gunther<sup>125</sup>, B. Guo<sup>158</sup>, J. Guo<sup>34</sup>, A. Gupta<sup>30</sup>, Y. Gusakov<sup>65</sup>, V.N. Gushchin<sup>128</sup>, A. Guindon<sup>54</sup>, H. Guler<sup>85,k</sup>, J. Gunther<sup>125</sup>, B. Guo<sup>158</sup>, J. Guo<sup>34</sup>, A. Gupta<sup>30</sup>, Y. Gusakov<sup>65</sup>, V.N. Gushchin<sup>128</sup>, A. Guindon<sup>54</sup>, H. Guler<sup>85,k</sup>, J. Gunther<sup>125</sup>, B. Guo<sup>158</sup>, J. Guo<sup>1</sup> A. Gutierrez<sup>93</sup>, P. Gutierrez<sup>111</sup>, N. Guttman<sup>153</sup>, O. Gutzwiller<sup>172</sup>, C. Guyot<sup>136</sup>, C. Gwenlan<sup>118</sup>, C.B. Gwilliam<sup>73</sup>, A. Haas<sup>143</sup>, S. Haas<sup>29</sup>, C. Haber<sup>14</sup>, R. Hackenburg<sup>24</sup>, H.K. Hadavand<sup>39</sup>, D.R. Hadley<sup>17</sup>, P. Haefner<sup>99</sup>, F. Hahn<sup>29</sup>, S. Haider<sup>29</sup>, Z. Hajduk<sup>38</sup>, H. Hakobyan<sup>176</sup>, J. Haller<sup>54</sup>, K. Hamacher<sup>174</sup>, P. Hamal<sup>113</sup>, A. Hamilton<sup>49</sup>, S. Hamilton<sup>161</sup>, H. Han<sup>32a</sup>, L. Han<sup>32b</sup>, K. Hanagaki<sup>116</sup>, M. Hance<sup>120</sup>, C. Handel<sup>81</sup>, P. Hanke<sup>58a</sup>, C.J. Hansen<sup>166</sup>, J.R. Hansen<sup>35</sup>, J.B. Hansen<sup>35</sup>, P.H. Hansen<sup>35</sup>, P.H. Hansen<sup>35</sup>, P.H. Hansen<sup>35</sup>, P.H. Hansen<sup>36</sup>, G.A. Hare<sup>137</sup>, T. Harenberg<sup>174</sup>, C. Handel<sup>81</sup>, P. Hansen<sup>35</sup>, P.H. Hansen<sup>35</sup>, P.H. Hansen<sup>35</sup>, P.H. Hansen<sup>35</sup>, P.H. Hansen<sup>35</sup>, P.H. Hansen<sup>36</sup>, G.A. Hare<sup>137</sup>, T. Harenberg<sup>174</sup>, C. Handel<sup>81</sup>, P. Hansen<sup>87</sup>, P.H. Hansen<sup>88</sup>, P.H. Hansen<sup>88</sup>, P.H. Hansen<sup>89</sup>, P.H. H D. Harrington<sup>21</sup>, O.M. Harris<sup>138</sup>, K. Harrison<sup>17</sup>, J. Hartert<sup>48</sup>, F. Hartjes<sup>105</sup>, T. Haruyama<sup>66</sup>, A. Harvey<sup>56</sup>, S. Hasegawa<sup>101</sup>, Y. Hasegawa<sup>140</sup>, S. Hassani<sup>136</sup>, M. Hatch<sup>29</sup>, D. Hauff<sup>99</sup>, S. Haug<sup>16</sup>, M. Hauschild<sup>29</sup>, R. Hauser<sup>88</sup>, M. Havranek<sup>20</sup>, B.M. Hawes<sup>118</sup>, C.M. Hawkes<sup>17</sup>, R.J. Hawkings<sup>29</sup>, D. Hawkins<sup>163</sup>, T. Hayakawa<sup>67</sup>, D Hayden<sup>76</sup>, H.S. Hayward<sup>73</sup>, S.J. Haywood<sup>129</sup>, E. Hazen<sup>21</sup>, M. He<sup>32d</sup>, S.J. Head<sup>17</sup>, V. Hedberg<sup>79</sup>, L. Heelan<sup>7</sup>, S. Heim<sup>88</sup>, B. Heinemann<sup>14</sup>, S. Heisterkamp<sup>35</sup>, L. Helary<sup>4</sup>, M. Heldmann<sup>48</sup>, M. Heller<sup>115</sup>, S. Hellman<sup>146a,146b</sup>, C. Helsens<sup>11</sup>, R.C.W. Henderson<sup>71</sup>, M. Henke<sup>58a</sup>, A. Henrichs<sup>54</sup>, A.M. Henriques Correia<sup>29</sup>, S. Henrot-Versille<sup>115</sup>, F. Henry-Couannier<sup>83</sup>, C. Hensel<sup>54</sup>, T. Henß<sup>174</sup>, Y. Hernández Jiménez<sup>167</sup>, R. Herrberg<sup>15</sup>, A.D. Hershenhorn<sup>152</sup>, G. Herten<sup>48</sup>, R. Hertenberger<sup>98</sup>, L. Hervas<sup>29</sup>, N.P. Hessey<sup>105</sup>, A. Hidvegi<sup>146a</sup>, E. Higón-Rodriguez<sup>167</sup>, D. Hill<sup>5,\*</sup>, J.C. Hill<sup>27</sup>, N. Hill<sup>5</sup>, K.H. Hiller<sup>41</sup>, S. Hillert<sup>20</sup>, S.J. Hillier<sup>17</sup>, I. Hinchliffe<sup>14</sup>, E. Hines<sup>120</sup>, M. Hirose<sup>116</sup>, F. Hirsch<sup>42</sup>, D. Hirschbuehl<sup>174</sup>, J. Hobbs<sup>148</sup>, N. Hod<sup>153</sup>, M.C. Hodgkinson<sup>139</sup>, P. Hodgson<sup>139</sup>, A. Hoecker<sup>29</sup>, M.R. Hoeferkamp<sup>103</sup>, J. Hoffman<sup>39</sup>, D. Hoffman<sup>83</sup>, M. Hohlfeld<sup>81</sup>, M. Holder<sup>141</sup>, A. Holmes<sup>118</sup>, S.O. Holmgren<sup>146a</sup>, T. Holy<sup>127</sup>, J.L. Holzbauer<sup>88</sup>, Y. Homma<sup>67</sup>, L. Hooft van Huysduynen<sup>108</sup>, T. Horazdovsky<sup>127</sup>, C. Horn<sup>143</sup>, S. Horner<sup>48</sup>. K. Horton<sup>118</sup>, J-Y. Hostachy<sup>55</sup>, S. Hou<sup>151</sup>, M.A. Houlden<sup>73</sup>, A. Hoummada<sup>135a</sup>, J. Howarth<sup>82</sup>, D.F. Howell<sup>118</sup>, I. Hristova <sup>41</sup>, J. Hrivnac<sup>115</sup>, I. Hruska<sup>125</sup>, T. Hryn'ova<sup>4</sup>, P.J. Hsu<sup>175</sup>, S.-C. Hsu<sup>14</sup>, G.S. Huang<sup>111</sup>, Z. Hubacek<sup>127</sup>,

F. Hubaut<sup>83</sup>, F. Huegging<sup>20</sup>, T.B. Huffman<sup>118</sup>, E.W. Hughes<sup>34</sup>, G. Hughes<sup>71</sup>, R.E. Hughes-Jones<sup>82</sup>, M. Huhtinen<sup>29</sup>, P. Hurst<sup>57</sup>, M. Hurwitz<sup>14</sup>, U. Husemann<sup>41</sup>, N. Huseynov<sup>65,l</sup>, J. Huston<sup>88</sup>, J. Huth<sup>57</sup>, G. Iacobucci<sup>102a</sup>, G. Iakovidis<sup>9</sup>, M. Ibbotson<sup>82</sup>, I. Ibragimov<sup>141</sup>, R. Ichimiya<sup>67</sup>, L. Iconomidou-Fayard<sup>115</sup>, J. Idarraga<sup>115</sup>, M. Idzik<sup>37</sup>, P. Iengo<sup>102a,102b</sup>, O. Igonkina<sup>105</sup>, Y. Ikegami<sup>66</sup>, M. Ikeno<sup>66</sup>, Y. Ilchenko<sup>39</sup>, D. Iliadis<sup>154</sup>, D. Imbault<sup>78</sup>, M. Imhaeuser<sup>174</sup>, M. Imori<sup>155</sup>, T. Ince<sup>20</sup>, J. Inigo-Golfin<sup>29</sup>, P. Ioannou<sup>8</sup>, M. Iodice<sup>134a</sup>, G. Ionescu<sup>4</sup>, A. Irles Quiles<sup>167</sup>, K. Ishii<sup>66</sup>, A. Ishikawa<sup>67</sup>, M. Ishino<sup>66</sup>, R. Ishmukhametov<sup>39</sup>, C. Issever<sup>118</sup>, S. Istin<sup>18a</sup>, Y. Itoh<sup>101</sup>, A.V. Ivashin<sup>128</sup>, W. Iwanski<sup>38</sup>, H. Iwasaki<sup>66</sup>, J.M. Izen<sup>40</sup>, V. Izzo<sup>102a</sup>, B. Jackson<sup>120</sup>, J.N. Jackson<sup>73</sup>, P. Jackson<sup>143</sup>, M.R. Jaekel<sup>29</sup>, V. Jain<sup>61</sup>, K. Jakobs<sup>48</sup>, S. Jakobsen<sup>35</sup>, J. Jakubek<sup>127</sup>, D.K. Jana<sup>111</sup>, E. Jankowski<sup>158</sup>, E. Jansen<sup>77</sup>, A. Jantsch<sup>99</sup>, M. Janus<sup>20</sup>, G. Jarlskog<sup>79</sup>, L. Leanty<sup>57</sup>, K. Jalan<sup>37</sup>, I. Janta Planta<sup>30</sup>, P. Janni<sup>29</sup>, A. Jarremio<sup>4</sup>, P. Jež<sup>35</sup>, S. Jázáguel<sup>4</sup>, M.K. Iba<sup>19a</sup>, H. Ii<sup>172</sup> S. Jakobsen<sup>35</sup>, J. Jakubek<sup>127</sup>, D.K. Jana<sup>111</sup>, E. Jankowski<sup>158</sup>, E. Jansen<sup>77</sup>, A. Jantsch<sup>99</sup>, M. Janus<sup>20</sup>, G. Jarlskog<sup>79</sup>, L. Jeanty<sup>57</sup>, K. Jelen<sup>37</sup>, I. Jen-La Plante<sup>30</sup>, P. Jenni<sup>29</sup>, A. Jeremie<sup>4</sup>, P. Jež<sup>35</sup>, S. Jézéquel<sup>4</sup>, M.K. Jha<sup>19a</sup>, H. Ji<sup>172</sup>, W. Ji<sup>81</sup>, J. Jia<sup>148</sup>, Y. Jiang<sup>32b</sup>, M. Jimenez Belenguer<sup>41</sup>, G. Jin<sup>32b</sup>, S. Jin<sup>32a</sup>, O. Jinnouchi<sup>157</sup>, M.D. Joergensen<sup>35</sup>, D. Joffe<sup>39</sup>, L.G. Johansen<sup>13</sup>, M. Johansen<sup>146a,146b</sup>, K.E. Johansson<sup>146a</sup>, P. Johansson<sup>139</sup>, S. Johnert<sup>41</sup>, K.A. Johns<sup>6</sup>, K. Jon-And<sup>146a,146b</sup>, G. Jones<sup>82</sup>, R.W.L. Jones<sup>71</sup>, T.W. Jones<sup>77</sup>, T.J. Jones<sup>73</sup>, O. Jonsson<sup>29</sup>, C. Joram<sup>29</sup>, P.M. Jorge<sup>124a,b</sup>, J. Joseph<sup>14</sup>, X. Ju<sup>130</sup>, V. Juranek<sup>125</sup>, P. Jussel<sup>62</sup>, V.V. Kabachenko<sup>128</sup>, S. Kabana<sup>16</sup>, M. Kaci<sup>167</sup>, A. Kaczmarska<sup>38</sup>, P. Kadlecik<sup>35</sup>, M. Kado<sup>115</sup>, H. Kagan<sup>109</sup>, M. Kagan<sup>57</sup>, S. Kaiser<sup>99</sup>, E. Kajomovitz<sup>152</sup>, S. Kalinin<sup>174</sup>, L.V. Kalinovskaya<sup>65</sup>, S. Kama<sup>39</sup>, N. Kanaya<sup>155</sup>, M. Kaneda<sup>155</sup>, T. Kanno<sup>157</sup>, V.A. Kantserov<sup>96</sup>, J. Kanzaki<sup>66</sup>, B. Kaplan<sup>175</sup>, A. Kapliy<sup>30</sup>, J. Kaplon<sup>29</sup>, D. Kar<sup>43</sup>, M. Karagoz<sup>118</sup>, M. Karnevskiy<sup>41</sup>, K. Karr<sup>5</sup>, V. Kartvelishvili<sup>71</sup>, A.N. Karyukhin<sup>128</sup>, L. Kashif<sup>172</sup>, A. Kasmi<sup>39</sup>, R.D. Kass<sup>109</sup>, A. Kastanas<sup>13</sup>, M. Kataoka<sup>4</sup>, Y. Kataoka<sup>155</sup>, E. Katsoufis<sup>9</sup>, J. Katzy<sup>41</sup>, V. Kaushik<sup>6</sup>, K. Kawagoe<sup>67</sup>, T. Kawamoto<sup>155</sup>, G. Kawamura<sup>81</sup>, M.S. Kayl<sup>105</sup>, V.A. Kazanin<sup>107</sup>, M.Y. Kazarinov<sup>65</sup>, S.I. Kazi<sup>86</sup>, J.R. Keates<sup>82</sup>, R. Keeler<sup>169</sup>, R. Kehoe<sup>39</sup>, M. Keil<sup>54</sup>, G.D. Kekelidze<sup>65</sup>, M. Kelly<sup>82</sup>, J. Kennedy<sup>98</sup>, C.J. Kenney<sup>143</sup>, M. Kenyon<sup>53</sup>, O. Kepka<sup>125</sup>, N. Kerschen<sup>29</sup>, B.P. Kerševan<sup>74</sup>, S. Kersten<sup>174</sup>, K. Kessoku<sup>155</sup>, C. Ketterer<sup>48</sup>, M. Khakzad<sup>28</sup>, F. Khalil-zada<sup>10</sup>, H. Khandanyan<sup>165</sup>, B.P. Kerševan<sup>74</sup>, S. Kersten<sup>174</sup>, K. Kessoku<sup>155</sup>, C. Ketterer<sup>48</sup>, M. Khakzad<sup>28</sup>, F. Khalil-zada<sup>10</sup>, H. Khandanyan<sup>165</sup>, A. Khanov<sup>112</sup>, D. Kharchenko<sup>65</sup>, A. Khodinov<sup>148</sup>, A.G. Kholodenko<sup>128</sup>, A. Khomich<sup>58a</sup>, T.J. Khoo<sup>27</sup>, A. Khanov<sup>112</sup>, D. Kharchenko<sup>65</sup>, A. Khodinov<sup>148</sup>, A.G. Kholodenko<sup>128</sup>, A. Khomich<sup>58a</sup>, T.J. Khoo<sup>27</sup>, G. Khoriauli<sup>20</sup>, N. Khovanskiy<sup>65</sup>, V. Khovanskiy<sup>95</sup>, E. Khramov<sup>65</sup>, J. Khubua<sup>51</sup>, G. Kilvington<sup>76</sup>, H. Kim<sup>7</sup>, M.S. Kim<sup>2</sup>, P.C. Kim<sup>143</sup>, S.H. Kim<sup>160</sup>, N. Kimura<sup>170</sup>, O. Kind<sup>15</sup>, B.T. King<sup>73</sup>, M. King<sup>67</sup>, R.S.B. King<sup>118</sup>, J. Kirk<sup>129</sup>, G.P. Kirsch<sup>118</sup>, L.E. Kirsch<sup>22</sup>, A.E. Kiryunin<sup>99</sup>, D. Kisielewska<sup>37</sup>, T. Kittelmann<sup>123</sup>, A.M. Kiver<sup>128</sup>, H. Kiyamura<sup>67</sup>, E. Kladiva<sup>144b</sup>, J. Klaiber-Lodewigs<sup>42</sup>, M. Klein<sup>73</sup>, U. Klein<sup>73</sup>, K. Kleinknecht<sup>81</sup>, M. Klemetti<sup>85</sup>, A. Klier<sup>171</sup>, A. Klimentov<sup>24</sup>, R. Klingenberg<sup>42</sup>, E.B. Klinkby<sup>35</sup>, T. Klioutchnikova<sup>29</sup>, P.F. Klok<sup>104</sup>, S. Klous<sup>105</sup>, E.-E. Kluge<sup>58a</sup>, T. Kluge<sup>73</sup>, P. Kluit<sup>105</sup>, S. Kluth<sup>99</sup>, E. Kneringer<sup>62</sup>, J. Knobloch<sup>29</sup>, E.B.F.G. Knoops<sup>83</sup>, A. Knue<sup>54</sup>, B.R. Ko<sup>44</sup>, T. Kobayashi<sup>155</sup>, M. Kobel<sup>43</sup>, B. Koblitz<sup>29</sup>, M. Kocian<sup>143</sup>, A. Kocnar<sup>113</sup>, P. Kodys<sup>126</sup>, K. Köneke<sup>29</sup>, A.C. König<sup>104</sup>, S. Koenig<sup>81</sup>, L. Köpke<sup>81</sup>, F. Koetsveld<sup>104</sup>, P. Koevesarki<sup>20</sup>, T. Koffas<sup>29</sup>, E. Koffeman<sup>105</sup>, F. Kohn<sup>54</sup>, Z. Kohout<sup>127</sup>, T. Kohriki<sup>66</sup>, T. Koi<sup>143</sup>, T. Kokott<sup>20</sup>, G.M. Kolachev<sup>107</sup>, H. Kolanoski<sup>15</sup>, V. Kolesnikov<sup>65</sup>, L. Koll<sup>88</sup>, D. Kollar<sup>29</sup>, M. Kollefrath<sup>48</sup>, S.D. Kolva<sup>82</sup>, A. Komar<sup>94</sup>, L. Komaragiri<sup>142</sup> Z. Kohout<sup>127</sup>, T. Kohriki<sup>66</sup>, T. Koi<sup>143</sup>, T. Kokott<sup>20</sup>, G.M. Kolachev<sup>107</sup>, H. Kolanoski<sup>15</sup>, V. Kolesnikov<sup>65</sup>, I. Koletsou<sup>89a</sup>, J. Koll<sup>88</sup>, D. Kollar<sup>29</sup>, M. Kollefrath<sup>48</sup>, S.D. Kolya<sup>82</sup>, A.A. Komar<sup>94</sup>, J.R. Komaragiri<sup>142</sup>, T. Kondo<sup>66</sup>, T. Kono<sup>41,m</sup>, A.I. Kononov<sup>48</sup>, R. Konoplich<sup>108,n</sup>, N. Konstantinidis<sup>77</sup>, A. Kootz<sup>174</sup>, S. Koperny<sup>37</sup>, S.V. Kopikov<sup>128</sup>, K. Korcyl<sup>38</sup>, K. Kordas<sup>154</sup>, V. Koreshev<sup>128</sup>, A. Korn<sup>14</sup>, A. Korol<sup>107</sup>, I. Korolkov<sup>11</sup>, E.V. Korolkova<sup>139</sup>, V.A. Korotkov<sup>128</sup>, O. Kortner<sup>99</sup>, S. Kortner<sup>99</sup>, V.V. Kostyukhin<sup>20</sup>, M.J. Kotamäki<sup>29</sup>, S. Kotov<sup>99</sup>, V.M. Kotov<sup>65</sup>, A. Kotwal<sup>44</sup>, C. Kourkoumelis<sup>8</sup>, V. Kouskoura<sup>154</sup>, A. Koutsman<sup>105</sup>, R. Kowalewski<sup>169</sup>, H. Kowalski<sup>41</sup>, T.Z. Kowalski<sup>37</sup>, W. Kozanecki<sup>136</sup>, A.S. Kozhin<sup>128</sup>, V. Kral<sup>127</sup>, V.A. Kramarenko<sup>97</sup>, G. Kramberger<sup>74</sup>, O. Krasel<sup>42</sup>, M.W. Krasny<sup>78</sup>, A. Krasznahorkay<sup>108</sup>, J. Kraus<sup>88</sup>, A. Kreisel<sup>153</sup>, F. Krejci<sup>127</sup>, J. Kretzschmar<sup>73</sup>, N. Krieger<sup>54</sup>, P. Krieger<sup>158</sup>, K. Kroeninger<sup>54</sup>, H. Kroha<sup>99</sup>, J. Kroll<sup>120</sup>, J. Kroseberg<sup>20</sup>, J. Krstic<sup>12a</sup>, U. Kruchonak<sup>65</sup>, H. Krüger<sup>20</sup>, Z.V. Krumshteyn<sup>65</sup>, A. Kruth<sup>20</sup>, T. Kubota<sup>155</sup>, S. Kuehn<sup>48</sup>, A. Kugel<sup>58c</sup>, T. Kuhl<sup>174</sup>, D. Kuhn<sup>62</sup>, V. Kukhtin<sup>65</sup>, Y. Kulchitsky<sup>90</sup>, S. Kuleshov<sup>31b</sup>, C. Kummer<sup>98</sup>, M. Kuna<sup>78</sup>, N. Kundu<sup>118</sup>, J. Kunkle<sup>120</sup>, A. Kupco<sup>125</sup>, H. Kurashige<sup>67</sup>, M. Kurata<sup>160</sup>, Y.A. Kurochkin<sup>90</sup>, V. Kus<sup>125</sup>, W. Kuykendall<sup>138</sup>, M. Kuze<sup>157</sup>, P. Kuzhir<sup>91</sup>, O. Kvasnicka<sup>125</sup>, J. Kvita<sup>29</sup>, R. Kwee<sup>15</sup>, A. La Rosa<sup>29</sup>, L. La Rotonda<sup>36a,36b</sup>, L. Labarga<sup>80</sup>, J. Labbe<sup>4</sup>, S. Lablak<sup>135a</sup>, C. Lacasta<sup>167</sup>, F. Lacava<sup>132a,132b</sup>, H. Lacker<sup>15</sup>, D. Lacour<sup>78</sup>, V.R. Lacuesta<sup>167</sup>, E. Ladygin<sup>65</sup>, R. Lafaye<sup>4</sup>, B. Laforge<sup>78</sup>, T. Lagouri<sup>80</sup>, S. Lai<sup>48</sup>, E. Laisne<sup>55</sup>, M. Lamanna<sup>29</sup>, C.L. Lampen<sup>6</sup>, E. Ladygin<sup>65</sup>, R. Lafaye<sup>4</sup>, B. Laforge<sup>78</sup>, T. Lagouri<sup>80</sup>, S. Lai<sup>48</sup>, E. Laisne<sup>55</sup>, M. Lamanna<sup>29</sup>, C.L. Lampen<sup>6</sup>, W. Lampl<sup>6</sup>, E. Lancon<sup>136</sup>, U. Landgraf<sup>48</sup>, M.P.J. Landon<sup>75</sup>, H. Landsman<sup>152</sup>, J.L. Lane<sup>82</sup>, C. Lange<sup>41</sup>, W. Lampir, E. Lancon T., C. Langgar, M.F.J. Landon J. H. Landsman J. J.L. Lane C. C. Lange L. A.J. Lankford Lands J. F. Lanni K. Lantzsch V.V. Lapin Landsman J. J. L. Lapoire J. J. F. Lapoire Lange Lapoire E. Le Menedeu<sup>135</sup>, A. Lebedev<sup>54</sup>, C. Lebel<sup>35</sup>, T. LeCompte<sup>3</sup>, F. Ledroit-Guillon<sup>35</sup>, H. Lee<sup>135</sup>, J.S.H. Lee<sup>136</sup>, S.C. Lee<sup>151</sup>, L. Lee<sup>175</sup>, M. Lefebvre<sup>169</sup>, M. Legendre<sup>136</sup>, A. Leger<sup>49</sup>, B.C. LeGeyt<sup>120</sup>, F. Legger<sup>98</sup>, C. Leggett<sup>14</sup>, M. Lehmacher<sup>20</sup>, G. Lehmann Miotto<sup>29</sup>, X. Lei<sup>6</sup>, M.A.L. Leite<sup>23b</sup>, R. Leitner<sup>126</sup>, D. Lellouch<sup>171</sup>, J. Lellouch<sup>78</sup>, M. Leltchouk<sup>34</sup>, V. Lendermann<sup>58a</sup>, K.J.C. Leney<sup>145b</sup>, T. Lenz<sup>174</sup>, G. Lenzen<sup>174</sup>, B. Lenzi<sup>136</sup>, K. Leonhardt<sup>43</sup>, S. Leontsinis<sup>9</sup>, C. Leroy<sup>93</sup>, J-R. Lessard<sup>169</sup>, J. Lesser<sup>146a</sup>, C.G. Lester<sup>27</sup>, A. Leung Fook Cheong<sup>172</sup>, J. Levêque<sup>4</sup>, D. Levin<sup>87</sup>, L.J. Levinson<sup>171</sup>, M.S. Levitski<sup>128</sup>, M. Lewandowska<sup>21</sup>, G.H. Lewis<sup>108</sup>, M. Leyton<sup>15</sup>, B. Li<sup>83</sup>, H. Li<sup>172</sup>, S. Li<sup>32b</sup>, X. Li<sup>87</sup>, Z. Liang<sup>39</sup>, Z. Liang<sup>118,o</sup>, B. Liberti<sup>133a</sup>, P. Lichard<sup>29</sup>, M. Lichtnecker<sup>98</sup>, K. Lie<sup>165</sup>, W. Liebig<sup>13</sup>, R. Lifshitz<sup>152</sup>, J.N. Lilley<sup>17</sup>, C. Limbach<sup>20</sup>, A. Limosani<sup>86</sup>, M. Limper<sup>63</sup>, S.C. Lin<sup>151,p</sup>, F. Linde<sup>105</sup>, J.T. Linnemann<sup>88</sup>, E. Lipeles<sup>120</sup>, L. Lipinsky<sup>125</sup>, A. Lipniacka<sup>13</sup>, T.M. Liss<sup>165</sup>, D. Lissauer<sup>24</sup>, A. Lister<sup>49</sup>,

```
 \text{A.M. Litke}^{137}, \, \text{C. Liu}^{28}, \, \text{D. Liu}^{151,q}, \, \text{H. Liu}^{87}, \, \text{J.B. Liu}^{87}, \, \text{M. Liu}^{32b}, \, \text{S. Liu}^2, \, \text{Y. Liu}^{32b}, \, \text{M. Livan}^{119a,119b}, \, \text{M. Livan}^{119a,119b}, \, \text{M. Liu}^{32b}, \, \text{M. Liu}^{3
   S.S.A. Livermore<sup>118</sup>, A. Lleres<sup>55</sup>, S.L. Lloyd<sup>75</sup>, E. Lobodzinska<sup>41</sup>, P. Loch<sup>6</sup>, W.S. Lockman<sup>137</sup>, S. Lockwitz<sup>175</sup>, T. Loddenkoetter<sup>20</sup>, F.K. Loebinger<sup>82</sup>, A. Loginov<sup>175</sup>, C.W. Loh<sup>168</sup>, T. Lohse<sup>15</sup>, K. Lohwasser<sup>48</sup>, M. Lokajicek<sup>125</sup>,
 1. Lodgenkoetter-5, F.K. Loedinger-7, A. Loginov-15, C.W. Lon-15, T. Lohse-5, K. Lohwasser-15, M. Lokajicek-123, J. Loken 118, V.P. Lombardo 89a, R.E. Long-71, L. Lopes 124a,b, D. Lopez Mateos 34,r, M. Losada 162, P. Loscutoff 14, F. Lo Sterzo 132a,132b, M.J. Losty 159a, X. Lou-40, A. Lounis 115, K.F. Loureiro 162, J. Love-21, P.A. Love-71, A.J. Lowe 143,e, F. Lu-32a, L. Lu-39, H.J. Lubatti 138, C. Luci 132a,132b, A. Lucotte-55, A. Ludwig-43, D. Ludwig-41, I. Ludwig-48, J. Ludwig-48, F. Luehring-61, G. Luijckx 105, D. Lumb-48, L. Luminari 132a, E. Lund-117, B. Lund-Jensen 147, B. Lundberg-79, J. Lundberg 146a,146b, J. Lundquist-35, M. Lungwitz-81, A. Lupi 122a,122b, G. Lutz-99, D. Lynn-24, L. Lu-14, E. Lu-1
     J. Lys<sup>14</sup>, E. Lytken<sup>79</sup>, H. Ma<sup>24</sup>, L.L. Ma<sup>172</sup>, J.A. Macana Goia<sup>93</sup>, G. Maccarrone<sup>47</sup>, A. Macchiolo<sup>99</sup>, B. Maček<sup>74</sup>,
   J. Machado Miguens<sup>124a</sup>, D. Macina<sup>49</sup>, R. Mackeprang<sup>35</sup>, R.J. Madaras<sup>14</sup>, W.F. Mader<sup>43</sup>, R. Maenner<sup>58c</sup>,
   T. Maeno<sup>24</sup>, P. Mättig<sup>174</sup>, S. Mättig<sup>41</sup>, P.J. Magalhaes Martins<sup>124a,g</sup>, L. Magnoni<sup>29</sup>, E. Magradze<sup>51</sup>,
   Y. Mahalalel<sup>153</sup>, K. Mahboubi<sup>48</sup>, G. Mahout<sup>17</sup>, C. Maiani<sup>132a,132b</sup>, C. Maidantchik<sup>23a</sup>, A. Maio<sup>124a,b</sup>, S. Majewski<sup>24</sup>, Y. Makida<sup>66</sup>, N. Makovec<sup>115</sup>, P. Mal<sup>6</sup>, Pa. Malecki<sup>38</sup>, P. Malecki<sup>38</sup>, V.P. Maleev<sup>121</sup>, F. Malek<sup>55</sup>, U. Mallik<sup>63</sup>,
   D. Malon<sup>5</sup>, S. Maltezos<sup>9</sup>, V. Malyshev<sup>107</sup>, S. Malyukov<sup>65</sup>, R. Mameghani<sup>98</sup>, J. Mamuzic<sup>12b</sup>, A. Manabe<sup>66</sup>, L. Mandelli<sup>89a</sup>, I. Mandić<sup>74</sup>, R. Mandrysch<sup>15</sup>, J. Maneira<sup>124a</sup>, P.S. Mangeard<sup>88</sup>, I.D. Manjavidze<sup>65</sup>, A. Mann<sup>54</sup>,
 L. Mandell' R. Mandrysch J. Maneira L. Mangeard's, I.D. Manjavidze's, A. Mann's, P.M. Manning 137, A. Manousakis-Katsikakis<sup>8</sup>, B. Mansoulie 136, A. Manz 99, A. Mapelli 129, L. Mapelli 129, L. March 130, J.F. Marchand 130, F. Marchese 133a, 133b, G. Marchiori 130, M. Marcisovsky 125, A. Marin 131, C.P. Marino 140, F. Marroquim 130, R. Marshall 130, Z. Marshall 130, F.K. Martens 158, S. Marti-Garcia 167, A.J. Martin 175, B. Martin 175, B. Martin 175, B. Martin 175, B. Martin 170, J.P. Martin 190, J.P. Martin 130, J.P. Martin 130, M. Martin 131, A. Marzin 131, L. Masetti 131, T. Masehim 155, R. Markin 155, R. Markin 132, A. Marzin 131, L. Masetti 131, T. Masehim 155, R. Markin 155, R. Mark
   T. Mashimo<sup>155</sup>, R. Mashinistov<sup>94</sup>, J. Masik<sup>82</sup>, A.L. Maslennikov<sup>107</sup>, M. Maß<sup>42</sup>, I. Massa<sup>19a,19b</sup>, G. Massaro<sup>105</sup>,
   N. Massol<sup>4</sup>, A. Mastroberardino<sup>36a,36b</sup>, T. Masubuchi<sup>155</sup>, M. Mathes<sup>20</sup>, P. Matricon<sup>115</sup>, H. Matsumoto<sup>155</sup>, H. Matsunaga<sup>155</sup>, T. Matsushita<sup>67</sup>, C. Mattravers<sup>118,s</sup>, J.M. Maugain<sup>29</sup>, S.J. Maxfield<sup>73</sup>, D.A. Maximov<sup>107</sup>,
  E.N. May<sup>5</sup>, A. Mayne<sup>139</sup>, R. Mazini<sup>151</sup>, M. Mazur<sup>20</sup>, M. Mazzanti<sup>89a</sup>, E. Mazzoni<sup>122a,122b</sup>, S.P. Mc Kee<sup>87</sup>, A. McCarthy<sup>148</sup>, T.G. McCarthy<sup>28</sup>, N.A. McCubbin<sup>129</sup>, K.W. McFarlane<sup>56</sup>, J.A. Mcfayden<sup>139</sup>, H. McGlone<sup>53</sup>, G. Mchedlidze<sup>51</sup>, R.A. McLaren<sup>29</sup>, T. Mclaughlan<sup>17</sup>, S.J. McMann<sup>19</sup>, R.A. McPherson<sup>169,i</sup>,
   A. Meade<sup>84</sup>, J. Mechnich<sup>105</sup>, M. Mechtel<sup>174</sup>, M. Medinnis<sup>41</sup>, R. Meera-Lebbai<sup>111</sup>, T. Meguro<sup>116</sup>, R. Mehdiyev<sup>93</sup>,
 A. Meade<sup>97</sup>, J. Mechiner<sup>188</sup>, M. Mechiner<sup>188</sup>, M. Medinins<sup>188</sup>, R. Meera-Leobal<sup>188</sup>, T. Meguro<sup>188</sup>, R. Meinardt<sup>48</sup>, B. Meirose<sup>79</sup>, C. Melachrinos<sup>30</sup>, B.R. Mellado Garcia<sup>172</sup>, L. Mendoza Navas<sup>162</sup>, Z. Meng<sup>151,q</sup>, A. Mengarelli<sup>19a,19b</sup>, S. Menke<sup>99</sup>, C. Menot<sup>29</sup>, E. Meoni<sup>11</sup>, K.M. Mercurio<sup>57</sup>, P. Mermod<sup>118</sup>, L. Merola<sup>102a,102b</sup>, C. Meroni<sup>89a</sup>, F.S. Merritt<sup>30</sup>, A. Messina<sup>29</sup>, J. Metcalfe<sup>103</sup>, A.S. Mete<sup>64</sup>, S. Meuser<sup>20</sup>, C. Meyer<sup>81</sup>, J-P. Meyer<sup>136</sup>, J. Meyer<sup>173</sup>, J. Meyer<sup>54</sup>, T.C. Meyer<sup>29</sup>, W.T. Meyer<sup>64</sup>, J. Miao<sup>32d</sup>, S. Michal<sup>29</sup>, L. Micu<sup>25a</sup>, R.P. Middleton<sup>129</sup>, P. Miele<sup>29</sup>, S. Migas<sup>73</sup>, L. Mijović<sup>41</sup>, G. Mikenberg<sup>171</sup>, M. Milos<sup>125</sup>, R.P. Middleton<sup>129</sup>, P. Milos<sup>274</sup>, D.W. Milos<sup>143</sup>, R. J. Milos<sup>88</sup>, W. L. Milos<sup>57</sup>, A. Milos<sup>174</sup>, D.W. Milos<sup>143</sup>, R. J. Milos<sup>88</sup>, W. L. Milos<sup>57</sup>, A. Milos<sup>174</sup>, R. M. Milos<sup>174</sup>, R. M. Milos<sup>185</sup>, A. Milos<sup>187</sup>, A. Milos<sup>187</sup>, A. Milos<sup>188</sup>, W. L. Milos<sup>188</sup>, C. Milos<sup>187</sup>, A. Milos<sup>188</sup>, M. L. Milos<sup>188</sup>, R. P. Milos<sup>188</sup>, M. Milos<sup>188</sup>, M. L. Milos<sup>188</sup>, R. P. Milos<sup>188</sup>, M. L. Milos<sup>188</sup>, M. Milos<sup>188</sup>, M. L. Milos<sup>188</sup>, M. L. Milos<sup>188</sup>, M. Milos
   M. Mikestikova<sup>125</sup>, B. Mikulec<sup>49</sup>, M. Mikuž<sup>74</sup>, D.W. Miller<sup>143</sup>, R.J. Miller<sup>88</sup>, W.J. Mills<sup>168</sup>, C. Mills<sup>57</sup>, A. Milov<sup>171</sup>,
 M. Mikestikova<sup>2-3</sup>, B. Mikulec<sup>3</sup>, M. Mikuz<sup>1</sup>, D.W. Miller<sup>1-3</sup>, R.J. Miller<sup>1</sup>, W.J. Mills<sup>1</sup>, C. Mills<sup>1</sup>, A. M. Millstead<sup>146a,146b</sup>, D. Milstein<sup>171</sup>, A.A. Minaenko<sup>128</sup>, M. Miñano<sup>167</sup>, I.A. Minashvili<sup>65</sup>, A.I. Mincer<sup>108</sup>, B. Mindur<sup>37</sup>, M. Mineev<sup>65</sup>, Y. Ming<sup>130</sup>, L.M. Mir<sup>11</sup>, G. Mirabelli<sup>132a</sup>, L. Miralles Verge<sup>11</sup>, A. Misiejuk<sup>76</sup>, J. Mitrevski<sup>137</sup>, G.Y. Mitrofanov<sup>128</sup>, V.A. Mitsou<sup>167</sup>, S. Mitsui<sup>66</sup>, P.S. Miyagawa<sup>82</sup>, K. Miyazaki<sup>67</sup>, J.U. Mjörnmark<sup>79</sup>, T. Moa<sup>146a,146b</sup>, P. Mockett<sup>138</sup>, S. Moed<sup>57</sup>, V. Moeller<sup>27</sup>, K. Mönig<sup>41</sup>, N. Möser<sup>20</sup>, S. Mohapatra<sup>148</sup>, B. Mohn<sup>13</sup>, W. Mohr<sup>48</sup>, S. Mohrdieck-Möck<sup>99</sup>, A.M. Moisseev<sup>128,*</sup>, R. Moles-Valls<sup>167</sup>, M. Milli, R. Moles-Valls<sup>167</sup>, R. Moles-Valls<sup>167</sup>, R. Moles-Valls<sup>167</sup>, R. Moles-Valls<sup>167</sup>, R. Moles-Valls<sup>168</sup>, R. Moles-Valls<sup>169</sup>, R. Moles
   J. Molina-Perez<sup>29</sup>, L. Moneta<sup>49</sup>, J. Monk<sup>77</sup>, E. Monnier<sup>83</sup>, S. Montesano<sup>89a,89b</sup>, F. Monticelli<sup>70</sup>, S. Monzani<sup>19a,19b</sup>,
J. Molina-Perez<sup>29</sup>, L. Moneta<sup>49</sup>, J. Monk<sup>77</sup>, E. Monnier<sup>83</sup>, S. Montesano<sup>89a,89b</sup>, F. Monticelli<sup>70</sup>, S. Monzani<sup>19a,19b</sup>, R.W. Moore<sup>2</sup>, G.F. Moorhead<sup>86</sup>, C. Mora Herrera<sup>49</sup>, A. Moraes<sup>53</sup>, A. Morais<sup>124a,b</sup>, N. Morange<sup>136</sup>, G. Morello<sup>36a,36b</sup>, D. Moreno<sup>81</sup>, M. Moreno Llácer<sup>167</sup>, P. Morettini<sup>50a</sup>, M. Morii<sup>57</sup>, J. Morin<sup>75</sup>, Y. Morita<sup>66</sup>, A.K. Morley<sup>29</sup>, G. Mornacchi<sup>29</sup>, M-C. Morone<sup>49</sup>, S.V. Morozov<sup>96</sup>, J.D. Morris<sup>75</sup>, H.G. Moser<sup>99</sup>, M. Mosidze<sup>51</sup>, J. Moss<sup>109</sup>, R. Mount<sup>143</sup>, E. Mountricha<sup>9</sup>, S.V. Mouraviev<sup>94</sup>, E.J.W. Moyse<sup>84</sup>, M. Mudrinic<sup>12b</sup>, F. Mueller<sup>58a</sup>, J. Mueller<sup>123</sup>, K. Mueller<sup>20</sup>, T.A. Müller<sup>98</sup>, D. Muenstermann<sup>29</sup>, A. Muijs<sup>105</sup>, A. Muir<sup>168</sup>, Y. Munwes<sup>153</sup>, K. Murakami<sup>66</sup>, W.J. Murray<sup>129</sup>, I. Mussche<sup>105</sup>, E. Musto<sup>102a,102b</sup>, A.G. Myagkov<sup>128</sup>, M. Myska<sup>125</sup>, J. Nadal<sup>11</sup>, K. Nagai<sup>160</sup>, K. Nagano<sup>66</sup>, Y. Nagasaka<sup>60</sup>, A.M. Nairz<sup>29</sup>, Y. Nakahama<sup>115</sup>, K. Nakamura<sup>155</sup>, I. Nakano<sup>110</sup>, G. Nanava<sup>20</sup>, A. Napier<sup>161</sup>, M. Nash<sup>77,s</sup>, N.R. Nation<sup>21</sup>, T. Nattermann<sup>20</sup>, T. Naumann<sup>41</sup>, G. Navarro<sup>162</sup>, H.A. Neal<sup>87</sup>, E. Nebot<sup>80</sup>, P.Yu. Nechaeva<sup>94</sup>, A. Negri<sup>119a,119b</sup>, G. Negri<sup>29</sup>, S. Nektarijevic<sup>49</sup>, A. Nelson<sup>64</sup>, S. Nelson<sup>143</sup>, T.K. Nelson<sup>143</sup>, S. Nemecek<sup>125</sup>, P. Nemethy<sup>108</sup>, A.A. Nepomuceno<sup>23a</sup>, M. Nessi<sup>29,t</sup>, S.Y. Nesterov<sup>121</sup>, M.S. Neubauer<sup>165</sup>, A. Neusiedl<sup>81</sup>, R.M. Neves<sup>108</sup>, P. Nevski<sup>24</sup>, P.R. Newman<sup>17</sup>. R.B. Nickerson<sup>118</sup>. R. Nicolaidou<sup>130</sup>
     M.S. Neubauer<sup>165</sup>, A. Neusiedl<sup>81</sup>, R.M. Neves<sup>108</sup>, P. Nevski<sup>24</sup>, P.R. Newman<sup>17</sup>, R.B. Nickerson<sup>118</sup>, R. Nicolaidou<sup>136</sup>,
   L. Nicolas<sup>139</sup>, B. Nicquevert<sup>29</sup>, F. Niedercorn<sup>115</sup>, J. Nielsen<sup>137</sup>, T. Niinikoski<sup>29</sup>, A. Nikiforov<sup>15</sup>, V. Nikolaenko<sup>128</sup>,
  K. Nikolaev<sup>65</sup>, I. Nikolic-Audit<sup>78</sup>, K. Nikolopoulos<sup>24</sup>, H. Nilsen<sup>48</sup>, P. Nilsson<sup>7</sup>, Y. Ninomiya <sup>155</sup>, A. Nisati<sup>132a</sup>, T. Nishiyama<sup>67</sup>, R. Nisius<sup>99</sup>, L. Nodulman<sup>5</sup>, M. Nomachi<sup>116</sup>, I. Nomidis<sup>154</sup>, H. Nomoto<sup>155</sup>, M. Nordberg<sup>29</sup>, B. Nordkvist<sup>146a,146b</sup>, P.R. Norton<sup>129</sup>, J. Novakova<sup>126</sup>, M. Nozaki<sup>66</sup>, M. Nožička<sup>41</sup>, L. Nozka<sup>113</sup>, I.M. Nugent<sup>159a</sup>, A.-E. Nuncio-Quiroz<sup>20</sup>, G. Nunes Hanninger<sup>20</sup>, T. Nunnemann<sup>98</sup>, E. Nurse<sup>77</sup>, T. Nyman<sup>29</sup>, B.J. O'Brien<sup>45</sup>,
   S.W. O'Neale<sup>17</sup>,*, D.C. O'Neil<sup>142</sup>, V. O'Shea<sup>53</sup>, F.G. Oakham<sup>28</sup>, H. Oberlack<sup>99</sup>, J. Ocariz<sup>78</sup>, A. Ochi<sup>67</sup>, S. Oda<sup>155</sup>,
     S. Odaka<sup>66</sup>, J. Odier<sup>83</sup>, H. Ogren<sup>61</sup>, A. Oh<sup>82</sup>, S.H. Oh<sup>44</sup>, C.C. Ohm<sup>146a,146b</sup>, T. Ohshima<sup>101</sup>, H. Ohshita<sup>140</sup>,
     T.K. Ohska<sup>66</sup>, T. Ohsugi<sup>59</sup>, S. Okada<sup>67</sup>, H. Okawa<sup>163</sup>, Y. Okumura<sup>101</sup>, T. Okuyama<sup>155</sup>, M. Olcese<sup>50a</sup>,
```

A.G. Olchevski<sup>65</sup>, M. Oliveira<sup>124a,g</sup>, D. Oliveira Damazio<sup>24</sup>, E. Oliver Garcia<sup>167</sup>, D. Olivito<sup>120</sup>, A. Olszewski<sup>38</sup>, J. Olszowska<sup>38</sup>, C. Omachi<sup>67</sup>, A. Onofre<sup>124a,u</sup>, P.U.E. Onyisi<sup>30</sup>, C.J. Oram<sup>159a</sup>, M.J. Oreglia<sup>30</sup>, F. Orellana<sup>49</sup>, Y. Oren<sup>153</sup>, D. Orestano<sup>134a,134b</sup>, I. Orlov<sup>107</sup>, C. Oropeza Barrera<sup>53</sup>, R.S. Orr<sup>158</sup>, E.O. Ortega<sup>130</sup>, B. Osculati<sup>50a,50b</sup>, R. Ospanov<sup>120</sup>, C. Osuna<sup>11</sup>, G. Otero y Garzon<sup>26</sup>, J.P Ottersbach<sup>105</sup>, M. Ouchrif<sup>135d</sup>, F. Ould-Saada<sup>117</sup>, A. Ouraou<sup>136</sup>, Q. Ouyang<sup>32a</sup>, M. Owen<sup>82</sup>, S. Owen<sup>139</sup>, O.K. Øye<sup>13</sup>, V.E. Ozcan<sup>18a</sup>, N. Ozturk<sup>7</sup>, A. Pacheco Pages<sup>11</sup>, C. Padilla Aranda<sup>11</sup>, E. Paganis<sup>139</sup>, F. Paige<sup>24</sup>, K. Pajchel<sup>117</sup>, S. Palestini<sup>29</sup>, D. Pallin<sup>33</sup>, A. Palma<sup>124a,b</sup>, J.D. Palmer<sup>17</sup>, Y.B. Pan<sup>172</sup>, E. Panagiotopoulou<sup>9</sup>, B. Panes<sup>31a</sup>, N. Panikashvili<sup>87</sup>, S. Panitkin<sup>24</sup>, D. Pantea<sup>25a</sup>, M. Panuskova<sup>125</sup>, V. Paolone<sup>123</sup>, A. Paoloni<sup>133a,133b</sup>, A. Papadelis<sup>146a</sup>, Th.D. Papadopoulou<sup>9</sup>, A. Paramonov<sup>5</sup>, W. Park<sup>24,v</sup>, M.A. Parker<sup>27</sup>, F. Parodi<sup>50a,50b</sup>, J.A. Parsons<sup>34</sup>, U. Parzefall<sup>48</sup>, E. Pasqualucci<sup>132a</sup>, A. Passeri<sup>134a</sup>, F. Pastore<sup>134a,134b</sup>, Fr. Pastore<sup>29</sup>, G. Pásztor <sup>49,w</sup>, S. Pataraia<sup>172</sup>, N. Patel<sup>150</sup>, J.R. Pater<sup>82</sup>, S. Patricelli<sup>102a,102b</sup>, T. Pauly<sup>29</sup>, M. Pecsy<sup>144a</sup>, M.I. Pedraza Morales<sup>172</sup>, S.V. Peleganchuk<sup>107</sup>, H. Peng<sup>172</sup>, R. Pengo<sup>29</sup>, A. Penson<sup>34</sup>, J. Penwell<sup>61</sup>, M. Perantoni<sup>23a</sup>, K. Perez<sup>34,r</sup>, T. Perez Cavalcanti<sup>41</sup>, E. Perez Codina<sup>11</sup>, M.T. Pérez García-Estañ<sup>167</sup>, V. Perez Reale<sup>34</sup>, I. Peric<sup>20</sup>, L. Perini<sup>89a,89b</sup>, H. Pernegger<sup>29</sup>, R. Perrino<sup>72a</sup>, P. Perrodo<sup>4</sup>, S. Persembe<sup>3a</sup>, V. Perez Reale<sup>34</sup>, I. Peric<sup>25</sup>, L. Perini<sup>33,835</sup>, H. Pernegger<sup>25</sup>, R. Perrino<sup>124</sup>, P. Perrodo<sup>4</sup>, S. Persembe<sup>34</sup>, V.D. Peshekhonov<sup>65</sup>, O. Peters<sup>105</sup>, B.A. Petersen<sup>29</sup>, J. Petersen<sup>29</sup>, T.C. Petersen<sup>35</sup>, E. Petit<sup>83</sup>, A. Petridis<sup>154</sup>, C. Petridou<sup>154</sup>, E. Petrolo<sup>132a</sup>, F. Petrucci<sup>134a,134b</sup>, D. Petschull<sup>41</sup>, M. Petteni<sup>142</sup>, R. Pezoa<sup>31b</sup>, A. Phan<sup>86</sup>, A.W. Phillips<sup>27</sup>, P.W. Phillips<sup>129</sup>, G. Piacquadio<sup>29</sup>, E. Piccaro<sup>75</sup>, M. Piccinini<sup>19a,19b</sup>, A. Pickford<sup>53</sup>, S.M. Piec<sup>41</sup>, R. Piegaia<sup>26</sup>, J.E. Pilcher<sup>30</sup>, A.D. Pilkington<sup>82</sup>, J. Pina<sup>124a,b</sup>, M. Pinamonti<sup>164a,164c</sup>, A. Pinder<sup>118</sup>, J.L. Pinfold<sup>2</sup>, J. Ping<sup>32c</sup>, B. Pinto<sup>124a,b</sup>, O. Pirotte<sup>29</sup>, C. Pizio<sup>89a,89b</sup>, R. Placakyte<sup>41</sup>, M. Plamondon<sup>169</sup>, W.G. Plano<sup>82</sup>, M.-A. Pleier<sup>24</sup>, A.V. Pleskach<sup>128</sup>, A. Poblaguev<sup>24</sup>, S. Poddar<sup>58a</sup>, F. Podlyski<sup>33</sup>, L. Poggioli<sup>115</sup>, T. Poghosyan<sup>20</sup>, M. P. Li<sup>49</sup>, P. Li<sup>40</sup>, P. Li<sup>49</sup>, P. Li M. Pohl<sup>49</sup>, F. Polci<sup>55</sup>, G. Polesello<sup>119a</sup>, A. Policicchio<sup>138</sup>, A. Polini<sup>19a</sup>, J. Poll<sup>75</sup>, V. Polychronakos<sup>24</sup>, D.M. Pomarede<sup>136</sup>, D. Pomeroy<sup>22</sup>, K. Pommès<sup>29</sup>, L. Pontecorvo<sup>132a</sup>, B.G. Pope<sup>88</sup>, G.A. Popeneciu<sup>25a</sup>, D.M. Pomarede<sup>130</sup>, D. Pomeroy<sup>22</sup>, K. Pommes<sup>23</sup>, L. Pontecorvo<sup>1324</sup>, B.G. Pope<sup>65</sup>, G.A. Popeneciu<sup>234</sup>, D.S. Popovic<sup>12a</sup>, A. Poppleton<sup>29</sup>, X. Portell Bueso<sup>48</sup>, R. Porter<sup>163</sup>, C. Posch<sup>21</sup>, G.E. Pospelov<sup>99</sup>, S. Pospisil<sup>127</sup>, I.N. Potrap<sup>99</sup>, C.J. Potter<sup>149</sup>, C.T. Potter<sup>114</sup>, G. Poulard<sup>29</sup>, J. Poveda<sup>172</sup>, R. Prabhu<sup>77</sup>, P. Pralavorio<sup>83</sup>, S. Prasad<sup>57</sup>, R. Pravahan<sup>7</sup>, S. Prell<sup>64</sup>, K. Pretzl<sup>16</sup>, L. Pribyl<sup>29</sup>, D. Price<sup>61</sup>, L.E. Price<sup>5</sup>, M.J. Price<sup>29</sup>, P.M. Prichard<sup>73</sup>, D. Prieur<sup>123</sup>, M. Primavera<sup>72a</sup>, K. Prokofiev<sup>108</sup>, F. Prokoshin<sup>31b</sup>, S. Protopopescu<sup>24</sup>, J. Proudfoot<sup>5</sup>, X. Prudent<sup>43</sup>, H. Przysiezniak<sup>4</sup>, S. Psoroulas<sup>20</sup>, E. Ptacek<sup>114</sup>, J. Purdham<sup>87</sup>, M. Purohit<sup>24,v</sup>, P. Puzo<sup>115</sup>, Y. Pylypchenko<sup>117</sup>, J. Qian<sup>87</sup>, Z. Qian<sup>83</sup>, Z. Qian<sup>41</sup>, A. Quadt<sup>54</sup>, D.R. Quarrie<sup>14</sup>, W.B. Quayle<sup>172</sup>, F. Quinonez<sup>31a</sup>, M. Raas<sup>104</sup>, V. Radescu<sup>58b</sup>, B. Radics<sup>20</sup>, T. Rador<sup>18a</sup>, F. Ragusa<sup>89a,89b</sup>, G. Rahal<sup>177</sup>, A.M. Rahimi<sup>109</sup>, D. Rahm<sup>24</sup>, S. Rajagopalan<sup>24</sup>, M. Rammensee<sup>48</sup>, M. Rammes<sup>141</sup>, M. Ramstedt<sup>146a,146b</sup>, K. Randrianarivony<sup>28</sup>, P.N. Ratoff<sup>71</sup>, F. Rauscher<sup>98</sup>, E. Rauter<sup>99</sup>, M. Raymond<sup>29</sup>, A.L. Read<sup>117</sup>, D.M. Rebuzzi<sup>119a,119b</sup>, A. Redelbach<sup>173</sup>, G. Redlinger<sup>24</sup>, R. Reece<sup>120</sup>, K. Reeves<sup>40</sup>, A. Reichold<sup>105</sup>, E. Reinherz-Aronis<sup>153</sup>, A. Reinsch<sup>114</sup>, I. Reisinger<sup>42</sup>, D. Reljic<sup>12a</sup>, C. Rembser<sup>29</sup>, Z.L. Ren<sup>151</sup>, A. Renaud<sup>115</sup>, P. Renkel<sup>39</sup>, B. Rensch<sup>35</sup>, M. Rescigno<sup>132a</sup>, S. Resconi<sup>89a</sup>, B. Resconi<sup>89a</sup>, P. Reznicek<sup>98</sup>, R. Rezvani<sup>158</sup>, A. Richards<sup>77</sup>, R. Richter<sup>99</sup>, E. Richter-Was<sup>38,x</sup>, M. Ridel<sup>78</sup>, S. Rieke<sup>81</sup>, M. Rijpstra<sup>105</sup>, M. Rijssenbeek<sup>148</sup>, A. Rimoldi<sup>119a,119b</sup>, L. Rinaldi<sup>19a</sup>, R.R. Rios<sup>39</sup>, I. Riu<sup>11</sup>, G. Rivoltella<sup>89a,89b</sup>, F. Rizatdinova<sup>112</sup>, E. Rizvi<sup>75</sup>, S.H. Robertson<sup>85,i</sup>, A. Robichaud-Veronneau<sup>49</sup>, D. Robinson<sup>27</sup>, J.E.M. Robinson<sup>77</sup>, M. Robinson<sup>114</sup>, A. Robson<sup>53</sup>, J.G. Rocha de Lima<sup>106</sup>, C. Roda<sup>122a,122b</sup>, D. Roda Dos Santos<sup>29</sup>, S. Rodier<sup>80</sup>, D. Rodriguez Garcia<sup>15</sup>, A. Roe<sup>54</sup>, S. Roe<sup>29</sup>, O. Røhne<sup>117</sup>, V. Rojo<sup>1</sup>, S. Rolli<sup>161</sup>, A. Romaniouk<sup>96</sup>, V.M. Romanov<sup>65</sup>, G. Romeo<sup>26</sup>, D. Romero Maltrana<sup>31a</sup>, L. Roos<sup>78</sup>, E. Ros<sup>167</sup>, S. Rosati<sup>132a,132b</sup>, M. Rose<sup>76</sup>, V.M. Romanov<sup>93</sup>, G. Romeo<sup>26</sup>, D. Romero Maltrana<sup>314</sup>, L. Roos<sup>75</sup>, E. Ros<sup>167</sup>, S. Rosati<sup>1324,1325</sup>, M. Rose<sup>76</sup>, G.A. Rosenbaum<sup>158</sup>, E.I. Rosenberg<sup>64</sup>, P.L. Rosendahl<sup>13</sup>, L. Rosselet<sup>49</sup>, V. Rossetti<sup>11</sup>, E. Rossi<sup>102a,102b</sup>, L.P. Rossi<sup>50a</sup>, L. Rossi<sup>89a,89b</sup>, M. Rotaru<sup>25a</sup>, I. Roth<sup>171</sup>, J. Rothberg<sup>138</sup>, D. Rousseau<sup>115</sup>, C.R. Royon<sup>136</sup>, A. Rozanov<sup>83</sup>, Y. Rozen<sup>152</sup>, X. Ruan<sup>115</sup>, I. Rubinskiy<sup>41</sup>, B. Ruckert<sup>98</sup>, N. Ruckstuhl<sup>105</sup>, V.I. Rud<sup>97</sup>, G. Rudolph<sup>62</sup>, F. Rühr<sup>6</sup>, F. Ruggieri<sup>134a,134b</sup>, A. Ruiz-Martinez<sup>64</sup>, E. Rulikowska-Zarebska<sup>37</sup>, V. Rumiantsev<sup>91,\*</sup>, L. Rumyantsev<sup>65</sup>, K. Runge<sup>48</sup>, O. Runolfsson<sup>20</sup>, Z. Rurikova<sup>48</sup>, N.A. Rusakovich<sup>65</sup>, D.R. Rust<sup>61</sup>, J.P. Rutherfoord<sup>6</sup>, C. Ruwiedel<sup>14</sup>, P. Ruzicka<sup>125</sup>, Y.F. Ryadov<sup>121</sup>, V. Ryadovikov<sup>128</sup>, P. Ryan<sup>88</sup>, M. Rybar<sup>126</sup>, G. Rybkin<sup>115</sup>, N.C. Ryder<sup>118</sup>, P. Ruzicka<sup>125</sup>, Y.F. Ryadovikov<sup>128</sup>, P. Ryan<sup>88</sup>, M. Rybar<sup>126</sup>, G. Rybkin<sup>115</sup>, N.C. Ryder<sup>118</sup>, R. Rybar<sup>137</sup>, R. Rybar<sup>138</sup>, R. Rybar<sup>138</sup>, R. Rybar<sup>139</sup>, R. Rybar<sup>130</sup>, R. Rybar<sup>130</sup>, R. Rybar<sup>130</sup>, R. Rybar<sup>130</sup>, R. Rybar<sup>130</sup>, R. Rybar<sup>130</sup>, R. Rybar<sup>131</sup>, R. Rybar<sup>131</sup>, R. Rybar<sup>131</sup>, R. Rybar<sup>131</sup>, R. Rybar<sup>132</sup>, R. Rybar<sup>132</sup>, R. Rybar<sup>133</sup>, R. Rybar<sup>133</sup>, R. Rybar<sup>134</sup>, R. Rybar<sup>135</sup>, R. Rybar<sup>135</sup>, R. Rybar<sup>136</sup>, R. Rybar<sup>137</sup>, R. Rybar<sup>137</sup>, R. Rybar<sup>138</sup>, R. Rybar<sup>138</sup>, R. Rybar<sup>138</sup>, R. Rybar<sup>138</sup>, R. Rybar<sup>138</sup>, R. Rybar<sup>138</sup>, R. Rybar<sup>139</sup>, R. Rybar<sup>130</sup>, R. R S. Rzaeva<sup>10</sup>, A.F. Saavedra<sup>150</sup>, I. Sadeh<sup>153</sup>, H.F-W. Sadrozinski<sup>137</sup>, R. Sadykov<sup>65</sup>, F. Safai Tehrani<sup>132a,132b</sup>, S. Rzaeva<sup>10</sup>, A.F. Saavedra<sup>150</sup>, I. Sadeh<sup>153</sup>, H.F-W. Sadrozinski<sup>154</sup>, R. Sadykov<sup>55</sup>, F. Saiai ienrani<sup>155</sup>, G. Salamanna<sup>105</sup>, A. Salamon<sup>133a</sup>, M. Saleem<sup>111</sup>, D. Salihagic<sup>99</sup>, A. Salnikov<sup>143</sup>, J. Salt<sup>167</sup>, B.M. Salvachua Ferrando<sup>5</sup>, D. Salvatore<sup>36a,36b</sup>, F. Salvatore<sup>149</sup>, A. Salzburger<sup>29</sup>, D. Sampsonidis<sup>154</sup>, B.H. Samset<sup>117</sup>, H. Sandaker<sup>13</sup>, H.G. Sander<sup>81</sup>, M.P. Sanders<sup>98</sup>, M. Sandhoff<sup>174</sup>, P. Sandhu<sup>158</sup>, T. Sandoval<sup>27</sup>, R. Sandstroem<sup>105</sup>, S. Sandvoss<sup>174</sup>, D.P.C. Sankey<sup>129</sup>, A. Sansoni<sup>47</sup>, C. Santamarina Rios<sup>85</sup>, C. Santoni<sup>33</sup>, R. Santonico<sup>133a,133b</sup>, H. Santos<sup>124a</sup>, J.G. Saraiva<sup>124a,b</sup>, T. Sarangi<sup>172</sup>, E. Sarkisyan-Grinbaum<sup>7</sup>, F. Sarri<sup>122a,122b</sup>, G. Sartisohn<sup>174</sup>, O. Sasaki<sup>66</sup>, T. Sasaki<sup>66</sup>, N. Sasao<sup>68</sup>, I. Satsounkevitch<sup>90</sup>, G. Sauvage<sup>4</sup>, J.B. Sauvan<sup>115</sup>, P. Savard<sup>158,d</sup>, V. Savinov<sup>123</sup>, D.O. Savu<sup>29</sup>, P. Savva<sup>9</sup>, L. Sawyer<sup>24,j</sup>, D.H. Saxon<sup>53</sup>, L.P. Says<sup>33</sup>, C. Sbarra<sup>19a,19b</sup>, A. Sbrizzi<sup>19a,19b</sup>, O. Scallon<sup>93</sup>, D.A. Scannicchio<sup>163</sup>, J. Schaarschmidt<sup>115</sup>, P. Schacht<sup>99</sup>, U. Schäfer<sup>81</sup>, S. Schaepe<sup>20</sup>, S. Schaetzel<sup>58b</sup>, A.C. Schaffer<sup>115</sup>, D. Schaile<sup>98</sup>, R.D. Schamberger<sup>148</sup>, A.G. Schamov<sup>107</sup>, V. Scharf<sup>58a</sup>, V.A. Schegelsky<sup>121</sup>, D. Scheirich<sup>87</sup>, M.I. Scherzer<sup>14</sup>, C. Schiavi<sup>50a,50b</sup>, J. Schieck<sup>98</sup>, M. Schioppa<sup>36a,36b</sup>, S. Schlenker<sup>29</sup>, J.L. Schlereth<sup>5</sup>, E. Schmidt<sup>48</sup>, M.P. Schmidt<sup>175</sup>,\*, K. Schmieden<sup>20</sup>, C. Schmitt<sup>81</sup>, M. Schmitz<sup>20</sup>, A. Schöning<sup>58b</sup>, M. Schott<sup>29</sup>, D. Schouten<sup>142</sup>, J. Schovancova<sup>125</sup>, M. Schram<sup>85</sup>, C. Schroeder<sup>81</sup>, N. Schroer<sup>58c</sup>, S. Schuh<sup>29</sup>, G. Schuler<sup>29</sup>, J. Schultes<sup>174</sup>, H.-C. Schultz-Coulon<sup>58a</sup>, H. Schulz<sup>15</sup>, J.W. Schumacher<sup>20</sup>, M. Schumacher<sup>48</sup>, B.A. Schumm<sup>137</sup>,

Ph. Schune<sup>136</sup>, C. Schwanenberger<sup>82</sup>, A. Schwartzman<sup>143</sup>, Ph. Schwemling<sup>78</sup>, R. Schwienhorst<sup>88</sup>, R. Schwierz<sup>43</sup>, J. Schwindling<sup>136</sup>, W.G. Scott<sup>129</sup>, J. Searcy<sup>114</sup>, E. Sedykh<sup>121</sup>, E. Segura<sup>11</sup>, S.C. Seidel<sup>103</sup>, A. Seiden<sup>137</sup>, F. Seifert<sup>43</sup>, J.M. Seixas<sup>23a</sup>, G. Sekhniaidze<sup>102a</sup>, D.M. Seliverstov<sup>121</sup>, B. Sellden<sup>146a</sup>, G. Sellers<sup>73</sup>, M. Seman<sup>144b</sup>, N. Semprini-Cesari<sup>19a,19b</sup>, C. Serfon<sup>98</sup>, L. Serin<sup>115</sup>, R. Seuster<sup>99</sup>, H. Severini<sup>111</sup>, M.E. Sevior<sup>86</sup>, A. Sfyrla<sup>29</sup>, E. Shabalina<sup>54</sup>, M. Shamim<sup>114</sup>, L.Y. Shan<sup>32a</sup>, J.T. Shank<sup>21</sup>, Q.T. Shao<sup>86</sup>, M. Shapiro<sup>14</sup>, P.B. Shatalov<sup>95</sup>, L. Shaver<sup>6</sup>, C. Shaw<sup>53</sup>, K. Shaw<sup>164a,164c</sup>, D. Sherman<sup>175</sup>, P. Sherwood<sup>77</sup>, A. Shibata<sup>108</sup>, S. Shimizu<sup>29</sup>, M. Shimojima<sup>100</sup>, T. Shin<sup>56</sup>, A. Shmeleva<sup>94</sup>, M.J. Shochet<sup>30</sup>, D. Short<sup>118</sup>, M.A. Shupe<sup>6</sup>, P. Sicho<sup>125</sup>, A. Sidoti<sup>132a,132b</sup>, A. Siebel<sup>174</sup>, F. Siegert<sup>48</sup>, J. Siegrist<sup>14</sup>, Dj. Sijacki<sup>12a</sup>, O. Silbert<sup>171</sup>, J. Silva<sup>124a,b</sup>, Y. Silver<sup>153</sup>, D. Silvertein<sup>143</sup>, S.B. Silverstein<sup>146a</sup>, V. Simak<sup>127</sup>, O. Simard<sup>136</sup>, Lj. Simic<sup>12a</sup>, S. Simion<sup>115</sup>, B. Simmons<sup>77</sup>, M. Simonyan<sup>35</sup>. P. Sinervo<sup>158</sup>, N.B. Sinev<sup>114</sup>, V. Sipica<sup>141</sup>, G. Siragusa<sup>81</sup>, A.N. Sisakyan<sup>65</sup>, S.Yu. Sivoklokov<sup>97</sup>, J. Sjölin<sup>146a,146b</sup>, P. Sinervo<sup>158</sup>, N.B. Sinev<sup>114</sup>, V. Sipica<sup>141</sup>, G. Siragusa<sup>81</sup>, A.N. Sisakyan<sup>65</sup>, S.Yu. Sivoklokov<sup>97</sup>, J. Sjölin<sup>146a,146b</sup>, T.B. Sjursen<sup>13</sup>, L.A. Skinnari<sup>14</sup>, K. Skovpen<sup>107</sup>, P. Skubic<sup>111</sup>, N. Skvorodnev<sup>22</sup>, M. Slater<sup>17</sup>, T. Slavicek<sup>127</sup>, K. Sliwa<sup>161</sup>, T.J. Sloan<sup>71</sup>, J. Sloper<sup>29</sup>, V. Smakhtin<sup>171</sup>, S.Yu. Smirnov<sup>96</sup>, L.N. Smirnova<sup>97</sup>, O. Smirnova<sup>79</sup>, B.C. Smith<sup>57</sup>, D. Smith<sup>143</sup>, K.M. Smith<sup>53</sup>, M. Smizanska<sup>71</sup>, K. Smolek<sup>127</sup>, A.A. Snesarev<sup>94</sup>, S.W. Snow<sup>82</sup>, J. Snow<sup>111</sup>, J. Snuverink<sup>105</sup>, S. Snyder<sup>24</sup>, M. Soares<sup>124a</sup>, R. Sobie<sup>169,i</sup>, J. Sodomka<sup>127</sup>, A. Soffer<sup>153</sup>, C.A. Solans<sup>167</sup>, M. Solar<sup>127</sup>, J. Solc<sup>127</sup>, E. Soldatov<sup>96</sup>, U. Soldevila<sup>167</sup>, E. Solfaroli Camillocci<sup>132a,132b</sup>, A.A. Solodkov<sup>128</sup>, O.V. Solovyanov<sup>128</sup>, J. Sondericker<sup>24</sup>, N. Soni<sup>2</sup>, V. Sopko<sup>127</sup>, B. Sopko<sup>127</sup>, M. Sorbi<sup>89a,89b</sup>, M. Sosebee<sup>7</sup>, A. Soukharev<sup>107</sup>, S. Spagnolo<sup>72a,72b</sup>, F. Spanò<sup>34</sup>, R. Spighi<sup>19a</sup>, G. Spigo<sup>29</sup>, F. Spila<sup>132a,132b</sup>, E. Spiriti<sup>134a</sup>, R. Spiwoks<sup>29</sup>, M. Spousta<sup>126</sup>, T. Spreitzer<sup>158</sup>, B. Spurlock<sup>7</sup>, R.D. St. Denis<sup>53</sup>, T. Stahl<sup>141</sup>, J. Stahlman<sup>120</sup>, R. Stamen<sup>58a</sup>, E. Stanecka<sup>29</sup>, R.W. Stanek<sup>5</sup>, C. Stanescu<sup>134a</sup>, S. Stapnes<sup>117</sup>, E.A. Starchenko<sup>128</sup>, J. Stark<sup>55</sup>, P. Staroba<sup>125</sup>, P. Starovoitov<sup>91</sup>, A. Staude<sup>98</sup>, P. Stavina<sup>144a</sup>, G. Stavropoulos<sup>14</sup>, G. Steele<sup>53</sup>, P. Steinbach<sup>43</sup>, P. Steinberg<sup>24</sup>, L. Stekl<sup>127</sup>, B. Stelzer<sup>142</sup>, H.J. Stelzer<sup>41</sup>, O. Stelzer-Chilton<sup>159a</sup>, H. Stenzel<sup>52</sup>, K. Stevenson<sup>75</sup> P. Steinberg<sup>24</sup>, I. Stekl<sup>127</sup>, B. Stelzer<sup>142</sup>, H.J. Stelzer<sup>41</sup>, O. Stelzer-Chilton<sup>159a</sup>, H. Stenzel<sup>52</sup>, K. Stevenson<sup>75</sup> G.A. Stewart<sup>53</sup>, J.A. Stillings<sup>20</sup>, T. Stockmanns<sup>20</sup>, M.C. Stockton<sup>29</sup>, K. Stoerig<sup>48</sup>, G. Stoicea<sup>25a</sup>, S. Stonjek<sup>99</sup>, P. Strachota<sup>126</sup>, A.R. Stradling<sup>7</sup>, A. Straessner<sup>43</sup>, J. Strandberg<sup>87</sup>, S. Strandberg<sup>146a,146b</sup>, A. Strandlie<sup>117</sup>, M. Strang<sup>109</sup>, E. Strauss<sup>143</sup>, M. Strauss<sup>111</sup>, P. Strizenec<sup>144b</sup>, R. Ströhmer<sup>173</sup>, D.M. Strom<sup>114</sup>, J.A. Strong<sup>76,\*</sup>, P. Grandberg<sup>130</sup>, J. Grandberg<sup>131</sup>, J. Strauss<sup>143</sup>, R. Ströhmer<sup>174</sup>, D.M. Strom<sup>114</sup>, J.A. Strong<sup>76,\*</sup>, R. Ströhmer<sup>175</sup>, D.M. Strom<sup>114</sup>, J.A. Strong<sup>76,\*</sup>, R. Ströhmer<sup>176</sup>, J. Strom<sup>115</sup>, J. Strom<sup>116</sup>, R. Ströhmer<sup>177</sup>, D.M. Strom<sup>116</sup>, J. Strom<sup>117</sup>, D.M. Strom<sup>118</sup>, J. Strom<sup>118</sup>, R. Ströhmer<sup>179</sup>, D.M. Strom<sup>118</sup>, R. Ströhmer<sup>179</sup>, R. Ströhme R. Stroynowski<sup>39</sup>, J. Strube<sup>129</sup>, B. Stugu<sup>13</sup>, I. Stumer<sup>24</sup>, J. Stupak<sup>148</sup>, P. Sturm<sup>174</sup>, D.A. Soh<sup>151</sup>, D. D. Su<sup>143</sup>, HS. Subramania<sup>2</sup>, A. Succurro<sup>11</sup>, Y. Sugaya<sup>116</sup>, T. Sugimoto<sup>101</sup>, C. Suhr<sup>106</sup>, K. Suita<sup>67</sup>, M. Suk<sup>126</sup>, V.V. Sulin<sup>94</sup>, S. Sultansoy<sup>3d</sup>, T. Sumida<sup>29</sup>, X. Sun<sup>55</sup>, J.E. Sundermann<sup>48</sup>, K. Suruliz<sup>164a,164b</sup>, S. Sushkov<sup>11</sup>, G. Susinno<sup>36a,36b</sup>, M.R. Sutton<sup>139</sup>, Y. Suzuki<sup>66</sup>, Yu.M. Sviridov<sup>128</sup>, S. Swedish<sup>168</sup>, I. Sykora<sup>144a</sup>, T. Sykora<sup>126</sup>, B. Szeless<sup>29</sup>, J. Sánchez<sup>167</sup>, D. Ta<sup>105</sup>, K. Tackmann<sup>29</sup>, A. Taffard<sup>163</sup>, R. Tafirout<sup>159a</sup>, A. Taga<sup>117</sup>, N. Taiblum<sup>153</sup>, Y. Takahashi<sup>101</sup>, H. Takai<sup>24</sup>, R. Takashima<sup>69</sup>, H. Takeda<sup>67</sup>, T. Takeshita<sup>140</sup>, M. Talby<sup>83</sup>, A. Talyshev<sup>107</sup>, M.C. Tamsett<sup>24</sup>, J. Tanaka<sup>155</sup>, R. Tanaka<sup>115</sup>, S. Tanaka<sup>131</sup>, S. Tanaka<sup>66</sup>, Y. Tanaka<sup>100</sup>, K. Tani<sup>67</sup>, N. Tannoury<sup>83</sup>, G.P. Tappern<sup>29</sup>, S. Tapprogge<sup>81</sup>, D. Tardif<sup>158</sup>, S. Tarem<sup>152</sup>, F. Tarrade<sup>24</sup>, G.F. Tartarelli<sup>89a</sup>, P. Tas<sup>126</sup>, M. Tasevsky<sup>125</sup>, E. Tassi<sup>36a,36b</sup>, M. Tatarkhanov<sup>14</sup>, C. Taylor<sup>77</sup>, F.E. Taylor<sup>92</sup>, G.N. Taylor<sup>86</sup>, W. Taylor<sup>159b</sup>, M. Teixeira Dias Castanheira<sup>75</sup>, P. Teixeira-Dias<sup>76</sup>, K.K. Temming<sup>48</sup>, H. Ten Kate<sup>29</sup>, P.K. Teng<sup>151</sup>, S. Terada<sup>66</sup>, K. Terashi<sup>155</sup>, J. Terron<sup>80</sup>, M. Terwort<sup>41,m</sup>, M. Testa<sup>47</sup>, R.J. Teuscher<sup>158,i</sup>, C.M. Tevlin<sup>82</sup>, J. Thadome<sup>174</sup>, J. Therhaag<sup>20</sup>, T. Theveneaux-Pelzer<sup>78</sup>, M. Thioye<sup>175</sup>, S. Thoma<sup>48</sup>, J.P. Thomas<sup>17</sup>, E.N. Thompson<sup>84</sup>, P.D. Thompson<sup>17</sup>, P.D. Thompson<sup>158</sup>, A.S. Thompson<sup>53</sup>, E. Thomson<sup>120</sup>, M. Thomson<sup>27</sup>, R.P. Thun<sup>87</sup>, T. Tic<sup>125</sup>, V.O. Tikhomirov<sup>94</sup>, Y.A. Tikhonov<sup>107</sup>, C.J.W.P. Timmermans<sup>104</sup>, P. Tipton<sup>175</sup>, F.J. Tique Aires Viegas<sup>29</sup>, S. Tisserant<sup>83</sup>, J. Tobias<sup>48</sup>, B. Toczek<sup>37</sup>, T. Todorov<sup>4</sup>, S. Todorova-Nova<sup>161</sup>, B. Toggerson<sup>163</sup>, J. Tojo<sup>66</sup>, S. Tokár<sup>144a</sup>, S. Tisserant<sup>13</sup>, J. Todas<sup>25</sup>, B. Toczek<sup>25</sup>, T. Todorov<sup>3</sup>, S. Todorova-Nova<sup>31</sup>, B. Toggerson<sup>130</sup>, J. Tojo<sup>30</sup>, S. Tokar<sup>144</sup>, K. Tokunaga<sup>67</sup>, K. Tokushuku<sup>66</sup>, K. Tollefson<sup>88</sup>, M. Tomoto<sup>101</sup>, L. Tompkins<sup>14</sup>, K. Toms<sup>103</sup>, G. Tong<sup>32a</sup>, A. Tonoyan<sup>13</sup>, C. Topfel<sup>16</sup>, N.D. Topilin<sup>65</sup>, I. Torchiani<sup>29</sup>, E. Torrence<sup>114</sup>, E. Torró Pastor<sup>167</sup>, J. Toth<sup>83</sup>, w, F. Touchard<sup>83</sup>, D.R. Tovey<sup>139</sup>, D. Traynor<sup>75</sup>, T. Trefzger<sup>173</sup>, J. Treis<sup>20</sup>, L. Tremblet<sup>29</sup>, A. Tricoli<sup>29</sup>, I.M. Trigger<sup>159a</sup>, S. Trincaz-Duvoid<sup>78</sup>, T.N. Trinh<sup>78</sup>, M.F. Tripiana<sup>70</sup>, N. Triplett<sup>64</sup>, W. Trischuk<sup>158</sup>, A. Trivedi<sup>24</sup>, B. Trocmé<sup>55</sup>, C. Troncon<sup>89a</sup>, M. Trottier-McDonald<sup>142</sup>, A. Trzupek<sup>38</sup>, C. Tsarouchas<sup>29</sup>, J.C-L. Tseng<sup>118</sup>, M. Tsiakiris<sup>105</sup>, D. Trincatalan and the second secon P.V. Tsiareshka<sup>90</sup>, D. Tsionou<sup>4</sup>, G. Tsipolitis<sup>9</sup>, V. Tsiskaridze<sup>48</sup>, E.G. Tskhadadze<sup>51</sup>, I.I. Tsukerman<sup>95</sup>, V. Tsulaia<sup>123</sup>, J.-W. Tsung<sup>20</sup>, S. Tsuno<sup>66</sup>, D. Tsybychev<sup>148</sup>, A. Tua<sup>139</sup>, J.M. Tuggle<sup>30</sup>, M. Turala<sup>38</sup>, D. Turecek<sup>127</sup>, I. Turk Cakir<sup>3e</sup>, E. Turlay<sup>105</sup>, R. Turra<sup>89a,89b</sup>, P.M. Tuts<sup>34</sup>, A. Tykhonov<sup>74</sup>, M. Tylmad<sup>146a,146b</sup>, M. Tyndel<sup>129</sup>, H. Tyrvainen<sup>29</sup>, G. Tzanakos<sup>8</sup>, K. Uchida<sup>20</sup>, I. Ueda<sup>155</sup>, R. Ueno<sup>28</sup>, M. Ugland<sup>13</sup>, M. Uhlenbrock<sup>20</sup>, M. Uhrmacher<sup>54</sup>, F. Ukegawa<sup>160</sup>, G. Unal<sup>29</sup>, D.G. Underwood<sup>5</sup>, A. Undrus<sup>24</sup>, G. Unel<sup>163</sup>, Y. Unno<sup>66</sup>, D. Urbaniec<sup>34</sup>, E. Urkovsky<sup>153</sup>, P. Urrejola<sup>31a</sup>, G. Usai<sup>7</sup>, M. Uslenghi<sup>119a,119b</sup>, L. Vacavant<sup>83</sup>, V. Vacek<sup>127</sup>, B. Vachon<sup>85</sup>, S. Vahsen<sup>146</sup>, G. Unal<sup>29</sup>, D. W. Lenghi<sup>132</sup>, G. Usai<sup>7</sup>, M. Uslenghi<sup>119a,119b</sup>, L. Vacavant<sup>83</sup>, V. Vacek<sup>127</sup>, B. Vachon<sup>85</sup>, S. Vahsen<sup>147</sup>, D. Vacavant<sup>84</sup>, D. Vacavant<sup>85</sup>, V. Vacek<sup>128</sup>, D. Vacavant<sup>85</sup>, V. Vacek<sup>128</sup>, D. Vacavant<sup>88</sup>, V. Vacek<sup>128</sup>, D. Vaca C. Valderanis<sup>99</sup>, J. Valenta<sup>125</sup>, P. Valente<sup>132a</sup>, S. Valentinetti<sup>19a,19b</sup>, S. Valkar<sup>126</sup>, E. Valladolid Gallego<sup>167</sup>, S. Vallecorsa<sup>152</sup>, J.A. Valls Ferrer<sup>167</sup>, H. van der Graaf<sup>105</sup>, E. van der Kraaij<sup>105</sup>, R. Van Der Leeuw<sup>105</sup>, E. van der Poel<sup>105</sup>, D. van der Ster<sup>29</sup>, B. Van Eijk<sup>105</sup>, N. van Eldik<sup>84</sup>, P. van Gemmeren<sup>5</sup>, Z. van Kesteren<sup>105</sup>, I. van Vulpen<sup>105</sup>, W. Vandelli<sup>29</sup>, G. Vandoni<sup>29</sup>, A. Vaniachine<sup>5</sup>, P. Vankov<sup>41</sup>, F. Vannucci<sup>78</sup>, F. Varela Rodriguez<sup>29</sup>, R. Vari<sup>132a</sup>, E.W. Varnes<sup>6</sup>, D. Varouchas<sup>14</sup>, A. Vartapetian<sup>7</sup>, K.E. Varvell<sup>150</sup>, V.I. Vassilakopoulos<sup>56</sup>, F. Vazeille<sup>33</sup>, G. Vegni<sup>89a,89b</sup>, J.J. Veillet<sup>115</sup>, C. Vellidis<sup>8</sup>, F. Veloso<sup>124a</sup>, R. Veness<sup>29</sup>, S. Veneziano<sup>132a</sup>, A. Ventura<sup>72a,72b</sup>, D. Ventura<sup>138</sup>, M. Venturi<sup>48</sup>, N. Venturi<sup>16</sup>, V. Vercesi<sup>119a</sup>, M. Verducci<sup>138</sup>, W. Verkerke<sup>105</sup>, J.C. Vermeulen<sup>105</sup>, A. Vest<sup>43</sup>, M.C. Vetterli<sup>142</sup>, I. Vichou<sup>165</sup>, T. Vickey<sup>145b</sup>, G.H.A. Viehhauser<sup>118</sup>, S. Viel<sup>168</sup>, M. Villa<sup>19a</sup>, 19b,

M. Villaplana Perez<sup>167</sup>, E. Vilucchi<sup>47</sup>, M.G. Vincter<sup>28</sup>, E. Vinek<sup>29</sup>, V.B. Vinogradov<sup>55</sup>, M. Virchaux<sup>136,\*</sup>, S. Viret<sup>33</sup>, J. Virzi<sup>14</sup>, A. Vitale <sup>19a,19b</sup>, O. Vitells<sup>171</sup>, M. Viti<sup>41</sup>, I. Vivarelli<sup>48</sup>, F. Vives Vaque<sup>11</sup>, S. Vlachos<sup>9</sup>, M. Vlasak<sup>127</sup>, N. Vlasov<sup>20</sup>, A. Vogel<sup>20</sup>, P. Vokac<sup>127</sup>, G. Volpi<sup>47</sup>, M. Volpi<sup>11</sup>, G. Volpini<sup>89a</sup>, H. von der Schmitt<sup>99</sup>, J. von Loeben<sup>99</sup>, H. von Radziewski<sup>48</sup>, E. von Toerne<sup>20</sup>, V. Vorobel<sup>126</sup>, A.P. Vorobiev<sup>128</sup>, V. Vorwerk<sup>11</sup>, M. Vos<sup>167</sup>, R. Voss<sup>29</sup>, T.T. Voss<sup>174</sup>, J.H. Vossebeld<sup>73</sup>, A.S. Vovenko<sup>128</sup>, N. Vranjes<sup>12a</sup>, M. Vranjes Milosavljevic<sup>12a</sup>, V. Vrba<sup>125</sup>, M. Vreswijk<sup>105</sup>, T. Vu Anh<sup>81</sup>, R. Vuillermet<sup>29</sup>, I. Vukotic<sup>115</sup>, W. Wagner<sup>174</sup>, P. Wagner<sup>120</sup>, H. Wahlen<sup>174</sup>, J. Wakabayashi<sup>101</sup>, J. Walbersloh<sup>42</sup>, S. Walch<sup>87</sup>, J. Walder<sup>71</sup>, R. Walker<sup>98</sup>, W. Makewisk<sup>141</sup>, R. Wall<sup>175</sup>, P. Waller<sup>73</sup>, C. Wang<sup>44</sup>, H. Wang<sup>172</sup>, H. Wang<sup>32b</sup>, J. Wang<sup>151</sup>, J. Wang<sup>32d</sup>, J.C. Wang<sup>138</sup>, R. Wang<sup>103</sup>, S.M. Wats<sup>184</sup>, S. Watts<sup>28</sup>, A.T. Waugh<sup>150</sup>, B.M. Waugh<sup>77</sup>, J. Weber<sup>42</sup>, M. Weber<sup>192</sup>, M.S. Weber<sup>16</sup>, P. Weber<sup>54</sup>, A.R. Weidberg<sup>118</sup>, P. Weigell<sup>99</sup>, J. Weingarten<sup>54</sup>, C. Weiser<sup>48</sup>, H. Wellenstein<sup>22</sup>, P.S. Wells<sup>29</sup>, M. Wern<sup>47</sup>, T. Wenaus<sup>24</sup>, S. Wendler<sup>123</sup>, Z. Weng<sup>151,o</sup>, T. Wengler<sup>29</sup>, S. Wenig<sup>29</sup>, N. Wermes<sup>20</sup>, M. Werner<sup>48</sup>, P. Werner<sup>29</sup>, M. Werth<sup>163</sup>, M. Wessels<sup>58a</sup>, K. Whalen<sup>28</sup>, S.J. Wheeler-Ellis<sup>163</sup>, S.P. Whitaker<sup>21</sup>, A. White<sup>7</sup>, M.J. White<sup>86</sup>, S. White<sup>24</sup>, S.R. Whitehead<sup>118</sup>, D. Whiteson<sup>163</sup>, D. Whittington<sup>61</sup>, F. Wickelins, D. Wickel<sup>174</sup>, F.J. Wickens<sup>129</sup>, W. Wideumann<sup>172</sup>, M. Wielers<sup>129</sup>, P. Wienemann<sup>20</sup>, C. Wiglesworth<sup>73</sup>, L.A.M. Wikt<sup>48</sup>, P.A. Wijeratne<sup>77</sup>, A. Wildauer<sup>167</sup>, M.A. Wildet<sup>41,m</sup>, I. Wilhelm<sup>126</sup>, H.G. Wilkens<sup>29</sup>, J.Z. Willen<sup>88</sup>, S. Wilhelmann<sup>48</sup>, F. Winklmeier<sup>29</sup>, M. Wittgen<sup>143</sup>, M.W. Wolter<sup>38</sup>, H. Wolters<sup>38</sup>, H. Wolters<sup>38</sup>, F. Wingerter-Seez<sup>4</sup>, S. Winkelmann<sup>48</sup>, F. Winklmeier<sup>29</sup>, M. Wittgen<sup>44</sup>, A. W. Soush<sup>53</sup>, B. Wrona<sup>73</sup>, S. L. Wul<sup>72</sup>, X. Wul<sup>39</sup>, P. Xul<sup>39</sup>, G. Xul<sup>32</sup>

<sup>1</sup> University at Albany, Albany NY, United States of America

<sup>2</sup> Department of Physics, University of Alberta, Edmonton AB, Canada

- <sup>3</sup> (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Dumlupinar University, Kutahya; (c) Department of Physics, Gazi University, Ankara; (d) Division of Physics, TOBB University of Economics and Technology, Ankara; (e) Turkish Atomic Energy Authority, Ankara, Turkey
- $^4$  LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
- <sup>5</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
- <sup>6</sup> Department of Physics, University of Arizona, Tucson AZ, United States of America
- <sup>7</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
- <sup>8</sup> Physics Department, University of Athens, Athens, Greece
- <sup>9</sup> Physics Department, National Technical University of Athens, Zografou, Greece
- <sup>10</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>11</sup> Institut de Física d'Altes Energies and Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
- <sup>12</sup> (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- <sup>13</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway
- <sup>14</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
- $^{\rm 15}$  Department of Physics, Humboldt University, Berlin, Germany
- Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- <sup>17</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>18</sup> (a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul;
- (c) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
- <sup>19</sup> (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy

- <sup>20</sup> Physikalisches Institut, University of Bonn, Bonn, Germany
- <sup>21</sup> Department of Physics, Boston University, Boston MA, United States of America
- <sup>22</sup> Department of Physics, Brandeis University, Waltham MA, United States of America
- <sup>23</sup> (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- <sup>24</sup> Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- <sup>25</sup> (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania
- <sup>26</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>27</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>28</sup> Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>29</sup> CERN, Geneva, Switzerland
- <sup>30</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- <sup>31</sup> (a) Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>32</sup> (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China
- <sup>33</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
- <sup>34</sup> Nevis Laboratory, Columbia University, Irvington NY, United States of America
- <sup>35</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- <sup>36</sup> (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
- <sup>37</sup> Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
- <sup>38</sup> The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- <sup>39</sup> Physics Department, Southern Methodist University, Dallas TX, United States of America
- <sup>40</sup> Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- <sup>41</sup> DESY, Hamburg and Zeuthen, Germany
- <sup>42</sup> Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- <sup>43</sup> Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- <sup>44</sup> Department of Physics, Duke University, Durham NC, United States of America
- <sup>45</sup> SUPA School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>46</sup> Fachhochschule Wiener Neustadt, Wiener Neustadt, Austria
- <sup>47</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>48</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
- <sup>49</sup> Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>50</sup> (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- <sup>51</sup> Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia
- <sup>52</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>53</sup> SUPA School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>54</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- <sup>55</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- <sup>56</sup> Department of Physics, Hampton University, Hampton VA, United States of America
- <sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- <sup>58</sup> (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut,

Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik,

Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

- <sup>59</sup> Faculty of Science, Hiroshima University, Hiroshima, Japan
- <sup>60</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- <sup>61</sup> Department of Physics, Indiana University, Bloomington IN, United States of America
- 62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- <sup>63</sup> University of Iowa, Iowa City IA, United States of America
- <sup>64</sup> Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- <sup>65</sup> Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- <sup>66</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

- <sup>67</sup> Graduate School of Science, Kobe University, Kobe, Japan
- <sup>68</sup> Faculty of Science, Kyoto University, Kyoto, Japan
- <sup>69</sup> Kyoto University of Education, Kyoto, Japan
- <sup>70</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>71</sup> Physics Department, Lancaster University, Lancaster, United Kingdom
- <sup>72</sup> (a) INFN Sezione di Lecce; (b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
- <sup>73</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- <sup>74</sup> Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- <sup>75</sup> Department of Physics, Queen Mary University of London, London, United Kingdom
- <sup>76</sup> Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- <sup>77</sup> Department of Physics and Astronomy, University College London, London, United Kingdom
- <sup>78</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- <sup>79</sup> Fysiska institutionen, Lunds universitet, Lund, Sweden
- <sup>80</sup> Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
- <sup>81</sup> Institut für Physik, Universität Mainz, Mainz, Germany
- <sup>82</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>84</sup> Department of Physics, University of Massachusetts, Amherst MA, United States of America
- <sup>85</sup> Department of Physics, McGill University, Montreal QC, Canada
- <sup>86</sup> School of Physics, University of Melbourne, Victoria, Australia
- <sup>87</sup> Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- 88 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- 89 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>90</sup> B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- <sup>91</sup> National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- <sup>92</sup> Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- <sup>93</sup> Group of Particle Physics, University of Montreal, Montreal QC, Canada
- <sup>94</sup> P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- <sup>95</sup> Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- <sup>96</sup> Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- 97 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- $^{98}$  Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- <sup>100</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan
- <sup>101</sup> Graduate School of Science, Nagoya University, Nagoya, Japan
- 102 (a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- <sup>103</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- <sup>104</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- <sup>106</sup> Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- <sup>107</sup> Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
- 108 Department of Physics, New York University, New York NY, United States of America
- <sup>109</sup> Ohio State University, Columbus OH, United States of America
- <sup>110</sup> Faculty of Science, Okayama University, Okayama, Japan
- <sup>111</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- <sup>112</sup> Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- <sup>113</sup> Palacký University, RCPTM, Olomouc, Czech Republic
- <sup>114</sup> Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- <sup>115</sup> LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
- <sup>116</sup> Graduate School of Science, Osaka University, Osaka, Japan
- <sup>117</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>118</sup> Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>119</sup> (a) ÎNFN Sezione di Pavia; (b) Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
- <sup>120</sup> Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- <sup>121</sup> Petersburg Nuclear Physics Institute, Gatchina, Russia

- <sup>122</sup> (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>123</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- <sup>124</sup> (a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas LIP, Lisboa, Portugal; (b) Departamento
- de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- <sup>125</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
   <sup>126</sup> Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- <sup>127</sup> Czech Technical University in Prague, Praha, Czech Republic
- <sup>128</sup> State Research Center Institute for High Energy Physics, Protvino, Russia
- <sup>129</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>130</sup> Physics Department, University of Regina, Regina SK, Canada
- <sup>131</sup> Ritsumeikan University, Kusatsu, Shiga, Japan
- <sup>132</sup> (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- <sup>133</sup> (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- <sup>134</sup> (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
- <sup>135</sup> (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; (c) Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
- $^{136}$  DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
- <sup>137</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- <sup>138</sup> Department of Physics, University of Washington, Seattle WA, United States of America
- <sup>139</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>140</sup> Department of Physics, Shinshu University, Nagano, Japan
- <sup>141</sup> Fachbereich Physik, Universität Siegen, Siegen, Germany
- <sup>142</sup> Department of Physics, Simon Fraser University, Burnaby BC, Canada
- <sup>143</sup> SLAC National Accelerator Laboratory, Stanford CA, United States of America
- <sup>144</sup> (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- $^{145}$  (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- <sup>146</sup> (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
- <sup>147</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden
- <sup>148</sup> Department of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
- <sup>149</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>150</sup> School of Physics, University of Sydney, Sydney, Australia
- <sup>151</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>152</sup> Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
- <sup>153</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>154</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- <sup>155</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- <sup>156</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- <sup>157</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- <sup>158</sup> Department of Physics, University of Toronto, Toronto ON, Canada
- <sup>159</sup> (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
- <sup>160</sup> Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
- <sup>161</sup> Science and Technology Center, Tufts University, Medford MA, United States of America
- 162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- <sup>163</sup> Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- <sup>164</sup> (a) ÎNFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Fisica, Università di Udine, Udine, Italy
- <sup>165</sup> Department of Physics, University of Illinois, Urbana IL, United States of America
- <sup>166</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- <sup>167</sup> Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and

Departamento de Ingenierá Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of

Valencia and CSIC, Valencia, Spain

- <sup>168</sup> Department of Physics, University of British Columbia, Vancouver BC, Canada
- <sup>169</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- <sup>170</sup> Waseda University, Tokyo, Japan
- <sup>171</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- <sup>172</sup> Department of Physics, University of Wisconsin, Madison WI, United States of America
- <sup>173</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- <sup>174</sup> Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- <sup>175</sup> Department of Physics, Yale University, New Haven CT, United States of America
- <sup>176</sup> Yerevan Physics Institute, Yerevan, Armenia
- 177 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
- <sup>a</sup> Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas LIP, Lisboa, Portugal
- <sup>b</sup> Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
- $^{c}$  Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>d</sup> Also at TRIUMF, Vancouver BC, Canada
- <sup>e</sup> Also at Department of Physics, California State University, Fresno CA, United States of America
- f Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
- <sup>g</sup> Also at Department of Physics, University of Coimbra, Coimbra, Portugal
- <sup>h</sup> Also at Università di Napoli Parthenope, Napoli, Italy
- <sup>i</sup> Also at Institute of Particle Physics (IPP), Canada
- <sup>j</sup> Also at Louisiana Tech University, Ruston LA, United States of America
- <sup>k</sup> Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
- Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- $^{m}$  Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- <sup>n</sup> Also at Manhattan College, New York NY, United States of America
- $^{o}$  Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
- <sup>p</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>q</sup> Also at High Energy Physics Group, Shandong University, Shandong, China
- <sup>r</sup> Also at California Institute of Technology, Pasadena CA, United States of America
- <sup>s</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>t</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>u</sup> Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
- $^{v}$  Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- w Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- <sup>x</sup> Also at Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>y</sup> Also at Department of Physics, Oxford University, Oxford, United Kingdom
- $^{z}$  Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
- $^{aa}$  Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- <sup>ab</sup> Also at Department of Physics, Nanjing University, Jiangsu, China
- \* Deceased